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16. ABSTRACT

This paper evaluates and interprets the available scientific and technical information that EPA staff believes is most relevant to the review of primary (health) and secondary (welfare) National Ambient Air Quality Standards for sulfur oxides (SO_x) and presents staff recommendations on alternative approaches to reaffirming or revising the standards. The assessment is intended to bridge the gap between the scientific review in the EPA criteria document for particulate matter and sulfur oxides and the judgments required of the Administrator in setting ambient air quality standards for sulfur oxides.

The major recommendations of the staff paper include the following:

1) that the health and welfare data support the need for sulfur dioxide (SO_2) standards;

2) that the reaffirmation of the existing suite of primary and secondary SO_2 standards (annual, 24-hour, 3-hour) remains a reasonable policy choice;

3) that new data from controlled human exposure studies warrants consideration of a short-term (1-hour) standard;

4) that a short-term standard ($\leq$ 4-hours) to protect vegetation should be retained.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Sulfur Oxides Sulfur Dioxide Air Pollution Particulate Matter	Air Quality Standards	

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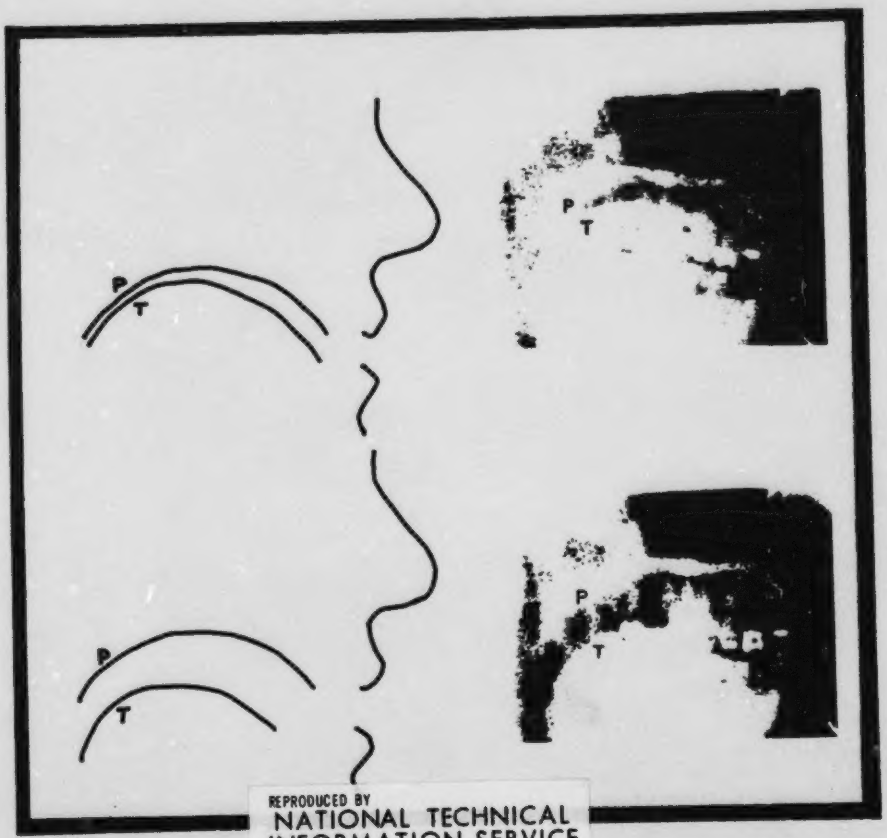
OAQPS Staff Paper



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The cover illustration shows two lateral views, represented schematically and by fluoroscope (x-ray), of the oral cavity during two breathing patterns. The top figures depict the mouth during typical oronasal breathing with a small air passage between the palate (P) and tongue (T). In this situation, much of the inhaled air enters through the the nose. The bottom figures depict hyperventilation, characterized by rapid oronasal breathing and an enlarged air space between the palate and tongue. Because the nose is very efficient in removing SO_2 , the relative penetration of SO_2 to more sensitive regions of the respiratory tract is largely dependent on the extent and character of the oral component of breathing under various conditions. This is an important consideration in evaluating controlled human exposure studies to SO_2 , which employ various types of breathing and levels of exercise.
Illustration courtesy of Dr. Donald Proctor.

This report has been reviewed by the Office of Air Quality Planning and Standards, EPA, and approved for publication. Mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use.

REVIEW OF THE NATIONAL AMBIENT AIR QUALITY STANDARDS FOR SULFUR OXIDES:

ASSESSMENT OF SCIENTIFIC AND TECHNICAL INFORMATION

OAQPS STAFF PAPER

Strategies and Air Standards Division
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, N.C. 27711

November, 1982

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Helpful comments and suggestions were also submitted by a number of independent scientists, by officials from the state agencies of California and Maine, by the Department of the Interior, and the Tennessee Valley Authority, and by environmental and industrial groups including the National Resources Defense Council, the National Audubon Society, the Environmental Defense Fund, the Non-Ferrous Smelter Companies, the American Petroleum Institute, and the Utility Air Regulatory Group.

TABLE OF CONTENTS

Page

List of Figures v

List of Tables vi

Executive Summary vii

I. Purpose 1

II. Background 1

III. Approach 3

IV. Air Quality Considerations 6

A. Chemical and Physical Characteristics 6

B. Ambient Concentrations 7

V. Critical Elements in the Review of the Primary Standards 14

A. Mechanisms 14

B. Effects of Concern 16

C. Sensitive Population Groups 29

D. Concentration/Response Information 34

VI. Factors to be Considered in Selecting Primary Standards for Sulfur Oxides 53

A. Pollutant Indicator, Averaging Times, and Form of the Standards 53

B. Level of the Standard 60

C. Summary of Staff Conclusions and Recommendations 83

VII. Critical Elements in the Review of the Secondary Standard.......... 88

A. Vegetation Damage 88

B. Materials Damage 115

C. Personal Comfort and Well-Being 124

Page

D. Acidic Deposition 125

E. Summary of Staff Conclusions and Recommendations 126

Appendix A. Factors that Influence Penetration and Deposition of SO_2 .... A-1

A. Inhalation Patterns A-1

B. Absorption by Particles A-5

C. Mechanisms of Toxicity A-7

Appendix B. Evaluation of Evidence for Effects on Respiratory Mechanics and Symptoms B-1

A. Controlled Human Exposure Studies of SO_2 Alone B-1

B. Long-term Exposures to SO_2 Alone B-6

C. SO_2 in Combination with Laboratory Particles, Other Gases B-6

D. Community Air Pollution B-10

Appendix C. Pulmonary Function Tests Used in Controlled Human Exposure Studies of SO_2 .... C-1

A. Introduction C-1

B. Glossary of Terms C-2

Appendix D. Analysis of Alternative Averaging Times and Exposure D-1

A. Analysis of SO_2 Air Quality Data D-1

B. Modeling Analysis D-7

C. Exposure Analysis D-11

Appendix E. CASAC Closure Memorandum E-1

References

LIST OF FIGURES

Number	Title	Page
4-1	Distribution of the Typical Hour of Maximum SO_2 among 153 Monitoring Locations, 1975-1978	12
4-2	Monthly Arithmetic Mean SO_2 Concentrations at Nonurban Sites in the Northeast	12
6-1	Factors Needed to Render a Multiple-Exceedance Standard Equivalent to a Single Exceedance Standard	59
6-2	Proportion of Sites Recording a Given Annual Average SO_2 Concentration, with 2 or more Short-Term SO_2 Concentrations Exceeding 0.5 ppm for 1-Hour or 0.14 ppm for 24 Hours	80
6-3	Proportion of Sites Recording a Given Second Maximum 24-Hour Average Concentration, with 2 or more 1-Hour SO_2 Concentrations Exceeding 0.5 ppm	80
7-1	Concentration-Response Relationships for the Minimum Concentration of SO_2 required to produce Foliar Injury	102
7-2	Corrosion Rate for Roofing and Siding (Large Sheets)	122
7-3	Corrosion Rate for Wire Fencing	122
D-1	Basic Relationships Between the Second Highest 1-Hour Value per Year and the Second Highest 24-Hour Value	D-4
D-2	Location and Number of Expected Exceedances per Year of a 1-Hour Average Value of 0.5 ppm for a 1000 MW Power Plant just Complying with a) the Current 24-Hour SO_2 Standard and b) the Current 3-Hour SO_2 Standard	D-8
D-3	Maximum 5 Concentrations for a 1000 MW Power Plant just Complying with a) the Current 24-Hour SO_2 Standard and b) the Current 3-Hour SO_2 Standard	D-10

LIST OF TABLES

Number	Title	Page
1	Staff Assessment of Key Controlled Human Exposure Studies......	xii
2	Staff Assessment of Short-Term Epidemiological Studies.........	xiv
4-1a	Characterization of SO_2 Levels (in ppm) at Population-Oriented Monitoring Sites for Different Averaging Times	9
4-1b	Approximate Conversion of ppm to $\mu g/m^3$	9
4-2	Characterization of SO_2 Levels (in ppm) at Source-Oriented Monitoring Sites for Different Averaging Times	11
5-1	Effects of SO_2 on Respiratory Mechanics and Symptoms	20
5-2	Major Sensitive Population Subgroups	30
5-3	Comparison of Responses in Normals, Atopics, and Asthmatics to SO_2	32
5-4	Selected Controlled Human Studies of Quantitative Interest	38
5-5	Summary of Epidemiological Studies Providing Most Useful Concentration/Response Information for Short-Term SO_2 Exposures	48
6-1	Staff Evaluation of Key Controlled Human Exposure Studies	62
6-2	Triggers of Asthmatic Attacks	67
6-3	Staff Assessment of Short-Term Epidemiological Studies	72
7-1	Controlled SO_2 Exposure Studies	93
7-2	Effects of Single 4-Hour SO_2 Exposure Mixtures on Foliar Injury	96
7-3	Controlled Exposure Studies of Long-Term Exposures to Pollutant Mixtures	98
7-4	Field Studies of Chronic Ambient SO_2 Exposures	106
7-5	Staff Assessment of Short-Term Vegetation Studies	111
A-1	Oronasal Distribution of Inspired Air	A-4
D-1	Current Status of Second High 1-Hour Values Versus Second Highest 24-Hour Values in Terms of Site Years	D-3
D-2	Current Status of Annual Averages Versus Second-Highest 24-Hour Values by Site Type	D-6

EXECUTIVE SUMMARY

This paper evaluates and interprets the available scientific and technical information that the EPA staff believes is most relevant to the review of primary (health) and secondary (welfare) National Ambient Air Quality Standards (NAAQS) for sulfur oxides and presents staff recommendations on alternative approaches to revising the standards.* Review of the NAAQS is a periodic process instituted to ensure the scientific adequacy of air quality standards and is required by Section 109 of the 1977 Clean Air Amendments. The assessment in this staff paper is intended to help bridge the gap between the scientific review contained in the EPA criteria document "Air Quality Criteria for Particulate Matter and Sulfur Oxides" and the judgments required of the Administrator in setting ambient standards for sulfur oxides. The staff paper is, therefore, an important element in the standards review process and provides an opportunity for public comment on proposed staff recommendations before they are presented to the Administrator. The focus of this paper is on sulfur dioxide (SO_2), alone and in combination with other pollutants.

SO_2 is a rapidly diffusing reactive gas that is quite soluble in water. It is emitted principally from combustion or processing of sulfur containing fossil fuels and ores. SO_2 occurs in the atmosphere with a variety of particles and other gases, and undergoes chemical and physical interactions with them forming sulfates and other transformation products.

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*The current standards for sulfur dioxide (SO_2) are: primary, 0.03 ppm (80 $\mu g/m^3$) annual arithmetic mean and 0.14 ppm (365 $\mu g/m^3$) 24-hour average not to be exceeded more than once per year; and, secondary, 0.5 ppm (1300 $\mu g/m^3$) 3-hour average not to be exceeded more than once per year.

At elevated concentrations, SO_2 can adversely affect human health, vegetation, materials, economic values, and personal comfort and well-being. SO_2 and its transformation products also are a major component of pollution related acidic deposition and visibility degradation. Long-term average SO_2 levels range from less than 0.004 ppm in remote rural sites to over 0.03 ppm in the most polluted urban industrial areas. The highest short-term values are found in the vicinity ($<$ 20 km) of major point sources. At such sites, maximum short-term levels for 24-hour, 3-hour, and 1-hour averages can exceed 0.4 ppm, 1.4 ppm, and 2.3 ppm, respectively.

Primary Standards

The staff has reviewed scientific and technical information on the known and potential health effects of SO_2 cited in the criteria document. The information includes studies of mechanisms of toxicity, effects of high exposures to SO_2, alone and in combination with particles and pollutant gases, in controlled human and animal studies; epidemiological studies of community air pollution; and air quality information. Based on this review, the staff derives the following conclusions:

1) Due to its high solubility, SO_2 is readily removed in the moist surfaces of the nose and other respiratory passages. With quiescent nasal breathing, almost all inhaled SO_2 is removed in the extrathoracic (head) region. This limits the potential for effects on the more sensitive thoracic regions of the respiratory tract. Factors that can increase penetration of SO_2 to these regions

include mouth and oronasal breathing, increased ventilation rates, and the presence of high levels of particles or fog droplets that may act as "carriers" for SO_2.

2) Although SO_2 may produce effects through several mechanisms, the most striking acute effects observed appear to result from stimulation of receptors in the tracheobronchial region leading to a reflex bronchoconstriction mediated by the nervous system.

3) The major effects categories of concern associated with high exposures to SO_2 include: (a) sensory and other non-respiratory responses, (b) effects on respiratory mechanics and symptoms, (c) aggravation of existing respiratory and cardiovascular disease, (d) effects on clearance and other host defense mechanisms, and (e) mortality.

4) The major subgroups of the population that appear likely to be most sensitive to the effects of SO_2 include: (a) asthmatics, (b) individuals not diagnosed as asthmatic but with atopic disorders (e.g., allergies), and (c) individuals with chronic obstructive pulmonary or cardiovascular disease. Other subgroups that may be somewhat sensitive include the elderly and children.

5) Although a number of animal, controlled human, and community epidemiological studies provide important qualitative information on the range of possible responses to SO_2, the most useful concentration-response information comes from a few very recent controlled human exposure studies and a limited set of epidemiological studies reflecting British air pollution exposures in the 1960's and early 1970's.

Based on the scientific and technical review as well as policy considerations, the staff makes the following recommendations and conclusions with respect to primary SO_2 standards:

1) Laboratory studies show that peak ambient levels of SO_2, acting alone, can cause health effects in humans. Consequently, a separate SO_2 standard is still appropriate. Because the range of possible SO_2 pollution interactions may not be well captured by an SO_2-particle index, and because separate particle and SO_2 standards can be chosen with due consideration to potential interactive effects, the additional complexities involved in specifying combination SO_2/particle standards do not appear warranted in terms of public health protection.

2) a) Retention of a standard with a 24-hour averaging time is recommended.

   b) Support for an annual standard at or near current levels is largely qualitative. Nevertheless, because short-term standards would not prevent increases in annual mean concentrations in some heavily populated urban areas, consideration should be given to retention of a primary annual standard for SO_2.

   c) Based on a series of recent controlled human studies, consideration of a new peak (1-hour) SO_2 standard is also recommended.

   d) The 24-hour and potential annual and 1-hour standards should all be expressed in statistical form; the decision on the allowable number of exceedances for the 24-hour and potential 1-hour standard should be made in conjunction with establishing levels for the standards.

3) a) The staff assessment of key controlled human studies of peak (minutes to an hour) SO_2 exposures is summarized in Table 1. The table focuses on those studies involving unencumbered or free breathing with exercise (chamber or facemask studies) and resting oral (mouthpiece) exposures. In so doing, the staff recognizes that caution must be used in extending the results of these laboratory exposures to ambient conditions; attention must be paid to the differences in natural oronasal and mouthpiece breathing, environmental conditions, and changes in SO_2 concentration with time. The major effects observed in these studies are increases in airway resistance and decreases in other functional measures indicative of significant bronchoconstriction in sensitive asthmatic or atopic subjects. At or above 0.5 ppm, changes in functional measures are accompanied by perceptible symptoms such as wheezing, shortness of breath, and coughing.

b) Based on this staff assessment, the range of 1-hour SO_2 levels of interest is 0.25 to 0.75 ppm (650 to 2000 $\mu g/m^3$). The lower bound represents a 1-hour level for which the maximum 5 to 10 minute peak exposures do not exceed 0.5 ppm, which is the lowest level where potentially significant responses in free (oronasal) breathing asthmatics have been reported in the published literature as of this writing. The upper bound of the range represents concentrations at which the risk of significant functional and symptomatic responses in exposed sensitive asthmatics and atopics appears high. In evaluating these data in the context of decision making on a possible 1-hour SO_2 standard, the following considerations are important: (a) the significance of the observed or anticipated responses to health, (b) the relative effect of SO_2

TABLE 1. STAFF ASSESSMENT OF KEY CONTROLLED HUMAN EXPOSURE STUDIES

SO_2 Concentration (5-60 minutes)	Observed Effects	Implications
1 ppm	Functional changes, possible symptoms in resting asthmatics, oral (facemask or mouthpiece) exposure.[1]	Strong suggestion that at this level even light exercise for "mouth" breathing asthmatics would result in comparable or more marked changes.[3]
0.75 ppm	Functional changes in free breathing normal healthy subjects, moderate to heavy exercise. No health effects.[2]	Comparable oronasal exposures in asthmatics, or atopics could result in effects of significance.[3]
	Functional changes, symptoms in free breathing (chamber) asthmatics, moderate exercise.[4]	Significant effects in mild asthmatics with moderate exercise.
0.5 ppm	Functional changes, symptoms in oronasal (facemask) breathing, asthmatics with moderate exercise but not in asthmatics (chamber) with light exercise.[5]	Lowest level of significant response for free breathing.
0.25 ppm	No observed effect in free breathing subjects.[3]	Significant effects unlikely.

[1] Sheppard et al. (1980), Koenig et al. (1980). The second study used SO_2 in combination with saline aerosol.

[2] Stacy et al. (1981); Bates and Hazucha (1973).

[3] Sheppard et al. (1981a); Linn et al. (1982a); Koenig et al. (1982a).

[4] Linn et al. (1982b).

[5] Kirkpatrick et al. (1982); Linn et al. (1982a).

compared to normal day to day variations in asthmatics from exercise and other stimuli, (c) the low probability of exposures of exercising asthmatics to peak levels, and (d) five to ten minute peak exposures may be a factor of two to three greater than hourly averages. Independent of frequency of exposure considerations, the upper bound of the range contains little or no margin of safety for exposed sensitive individuals. However, the limited geographical areas likely to be affected and low frequency of peak exposure to active asthmatics if the standard is met add to the margin of safety.

c) The data do not suggest other groups that are more sensitive than asthmatics to single peak exposures, but qualitative data suggest that repeated peaks might produce effects of concern in other sensitive individuals. Potential interactions of SO_2 and O_3 have not been investigated in asthmatics and atopics. The qualitative data, potential pollutant interactions, and other considerations listed above should be considered in determining the need for and evaluating the margin of safety provided by alternative 1-hour standards.

4) a) The staff assessment of the short-term (24-hour) epidemiological data is summarized in Table 2. The "effects likely" row denotes concentration ranges derived from the criteria document at or above which there appears greatest certainty that effects would occur. The data do not, however, show evidence of clear population thresholds, but suggest that effects may be possible at levels below those listed in the "effects likely" row; the evidence and risks at lower levels are, however, much less certain.

TABLE 2. STAFF ASSESSMENT OF SHORT-TERM EPIDEMIOLOGICAL STUDIES

Effects/ Study	Measured Sulfur Dioxide - μg/m^3(ppm) - 24 hour mean		
	Daily Mortality in London[1]	Aggravation of Bronchitis[2]	Combined Effects Levels
Effects Likely[3]	500-1000(0.19-0.38)	500-600(0.19-0.23)	500(0.19)
Effects Possible	-	< 500(0.19)	< 500(0.19)

[1] Deviations in daily mortality from mean levels examined in 3 studies encompassing individual London winters of 1958-59 and 14 aggregate winters from 1958-72. Early winters were dominated by high smoke and SO_2, principally from coal combustion emissions, and with frequent fogs (Martin and Bradley, 1960; Ware et al., 1981; Mazundar et al., 1981).

[2] Examination of symptoms reported by bronchitics in London. Studies conducted from the mid-1950's to the early 1970's (Lawther et al., 1970).

[3] CD, Table 14-8.

b) Based on this staff assessment, the range of 24-hour SO_2 levels of interest are 0.14 to 0.19 ppm (365 to 500 μg/m^3). Under the conditions prevailing during the London studies (high particles, frequent fogs, winter), the upper end of the range represents levels at which effects may be likely according to the criteria document. The risk of health effects should be lower when translating these results to U.S. settings with particle levels at or below the ambient standards.

c) The uncertainties with respect to interactive effects with particles or other pollutants and nature of effects are important margin of safety considerations. In the absence of quantitative scientific evidence for a well defined "no effects" level, the level of the current standard is recommended as a lower bound. This level was previously judged to provide an adequate margin of safety from the same effects under consideration here. Qualitative data from animal toxicology, controlled human studies and community epidemiology suggest risks of potential effects (e.g., slowed clearance) as well as the existence of sensitive groups (e.g., children) not evaluated in the more quantitative studies. These factors, as well as potential pollutant interactions, exposure characteristics, and whether the 24-hour standard is intended to act as a surrogate for a 1-hour standard, should also be considered in evaluating the margin of safety provided by 24-hour standards in the range of 0.14 to 0.19 ppm.

5) Although the data are inconclusive and uncertain, the possibility of effects from continuous lower level exposures to SO_2 cannot be ruled out. Given the lack of epidemiological data suggesting long-term effects of SO_2 at or near the levels of the current annual standard, however, no quantitative rationale can be offered to support a specific range of interest for an annual standard. Nevertheless, air quality analyses summarized in Appendix D suggest that short-term standards in the ranges recommended in this paper would not prevent annual levels in excess of the current standard in a limited number of heavily populated urban areas. Because of the possibility of effects from a large increase in population exposure, consideration should be given to maintaining a primary annual standard at or above the level of the current standard.

6) Analysis of alternative averaging times to date suggest that while any single standard might not be a suitable surrogate for other averaging times, implementation of the current suite of primary and secondary SO_2 standards (annual, 24-hour, 3-hour) provides substantial protection against the direct health and welfare effects identified

in the scientific literature as being associated with ground level SO_2 air quality. This permits the consideration of reaffirming the existing SO_2 standards as a reasonable policy option, following the current criteria and standards review. Factors favoring such an option include the substantial improvements likely in information on 1-hour effects over the next few years, the uncertainties in long-term effects data, the possibility of substantial changes in SO_2 control strategies prompted by regional effects, and the practical advantages of not requiring premature formulation and implementation of a new SO_2 regulatory program associated with revising standards at this time.

Secondary Standards

The staff examined information in the criteria document relevant to the review of the secondary standards. Categories of welfare effects examined include effects on vegetation, materials, personal comfort and well-being, and acid deposition. Major staff conclusions and recommendations are summarized below.

1) a) Damage to vegetation by SO_2, resulting in economic losses in commercial crops, aesthetic damage to cultivated trees, shrubs and other ornamentals, and reductions in productivity, species richness and diversity in natural ecosystems, constitute effects on public welfare in impacted areas. Such effects are associated with both peak and short-term (minutes to hours) and long-term (weeks to years) exposures to SO_2.

b) Given the available data on the acute effects of SO_2 on plants (growth and yield and foliar injury), a 3-hour standard at or below the level of the current secondary standard (0.5 ppm) may be needed to protect vegetation. If a 1-hour primary standard is chosen that provides equivalent or better protection, then the averaging time and level of the secondary standard can be made equal to the primary standard. In the absence of a primary standard that provides adequate protection for vegetation, a 3-hour secondary standard is recommended.

c) Available data on the effects of long-term SO_2 exposures of vascular plants (e.g., trees, shrubs, crops) suggest the possibility of changes in species richness and diversity, reduced growth over extended periods, and premature needle drop. However, these data are weak and not developed well enough to provide the principal basis for selecting the level of a long-term SO_2 standard. Existing information, thus, cannot be used to show significant effects on vascular plants at annual SO_2 levels below the current primary annual standard, but does support the need to protect against the effects of prolonged SO_2 exposure by limiting long-term SO_2 concentrations much above this level.

d) Current long-term SO_2 concentrations over large areas of the northeast exceed levels that may be associated with effects on non-vascular plants (e.g., lichens, mosses). Given uncertainties regarding the extent and importance of these potential effects on natural ecosystems and the regional character of the exposures, the staff recommends that the effects of SO_2 on non-vascular plants be considered in the larger context of regional acid deposition - visibility - fine particle strategies. As such, no separate long-term secondary standard for non-vascular plants is recommended at this time.

2) a) Elevated long-term SO_2 concentrations in the presence of moisture can damage a number of materials including: exposed metals, paints, building materials, statuary, paper, leather, and textiles. Control strategies have resulted in marked improvements in long-term SO_2 levels over the past 13 years, which the criteria document associates with substantial benefits. While the available data are limited and do not permit definitive findings with respect to the potential costs of SO_2 related material damage or provide clear quantitative relationships for the full range of potentially affected materials, they generally support the need for limiting long-term SO_2 concentrations in urban areas.

b) Analysis of existing air quality data suggests that without the primary annual standard, long-term urban air quality could deteriorate and in a number of large urban areas might exceed the current annual standard. Therefore, consideration should be given to a long-term secondary SO_2 standard at or below the level of the current annual primary standard of 0.03 ppm (80 $\mu g/m^3$) to protect against materials damage effects.

3) The staff concludes that a secondary SO_2 standard is not needed to protect against effects on personal comfort and well-being.

4) The available scientific information indicates that the current 3-hour and annual standards provide reasonable protection against the direct welfare effects associated with ambient SO_2. In essence, the data support maintenance of SO_2 standards at or below levels of the current standards.

5) The acid deposition issue will not be addressed directly in this review of the sulfur oxides standards.

REVIEW OF THE NATIONAL AMBIENT AIR QUALITY STANDARDS FOR SULFUR OXIDES: ASSESSMENT OF SCIENTIFIC AND TECHNICAL INFORMATION

OAQPS STAFF PAPER

I. PURPOSE

This paper evaluates and interprets the most relevant scientific and technical information reviewed in the draft EPA document "Air Quality Criteria for Particulate Matter and Sulfur Oxides" (EPA, 1982a) in order to better specify the critical elements which EPA staff believes should be considered in the possible revision of the primary and secondary National Ambient Air Quality Standards (NAAQS) for sulfur oxides. This assessment is intended to help bridge the gap between the scientific review contained in the criteria document and the judgments required of the Administrator in setting ambient standards for sulfur oxides. As such, particular emphasis is placed on identifying those conclusions and uncertainties in the available scientific literature that the staff believes should be considered in selecting averaging time, form, and level for the primary standards. While the paper should be of use to all parties interested in the standards review, it is written for those decision makers, scientists, and staff who have some familiarity with the technical discussions contained in the criteria document.

II. BACKGROUND

Since 1970 the Clean Air Act, as amended, has provided authority and guidance for the listing of certain ambient air pollutants which may endanger public health or welfare and the setting and revising of NAAQS for those pollutants. Primary standards must be based on health effects criteria and provide an adequate margin of safety to ensure protection of public health. As several recent judicial decisions have made clear, the economic and technological feasibility of attaining primary standards are not to be considered in setting them, although such factors may be considered to a degree in the development of state plans to implement the standards (D.C. Cir., 1980, 1981). Further guidance provided in the legislative history of the Act indicates that the standards should be set at "the maximum permissible ambient air level . . . which will protect the health of any [sensitive] group of the population." Also, margins of safety are to be provided such that the standards will afford "a reasonable degree of protection . . . against hazards which research has not yet identified" (Committee on Public Works, 1974). In the final analysis, the EPA Administrator must make a policy decision in setting the primary standard, based on his judgment regarding the implications of all the health effects evidence and the requirement that an adequate margin of safety be provided.

Secondary ambient air quality standards must be adequate to protect the public welfare from any known or anticipated adverse effects associated with the presence of a listed ambient air pollutant. Welfare effects, which are defined in section 302(h) of the Act, include effects on vegetation, visibility, water, crops, man-made materials, animals, economic values and personal comfort and well-being. In specifying a level or levels for secondary standards the Administrator must determine at which point the effects become "adverse" and base his judgment on the welfare effects criteria.

The current primary standards for sulfur oxides (to protect public health) are 0.03 parts per million (ppm or 80 micrograms per cubic meter

[$\mu g/m^3$]) annual arithmetic mean, and 0.14 ppm (365 $\mu g/m^3$), maximum 24-hour concentration not to be exceeded more than once per year. The current secondary standard for sulfur oxides (to protect public welfare) is 0.5 ppm (1300 $\mu g/m^3$), maximum 3-hour concentration, not to be exceeded more than once per year. For both primary and secondary standards, sulfur oxides are measured as sulfur dioxide (SO_2). Thus, SO_2 is the current indicator for the sulfur oxides standards.

Preliminary drafts of this paper were reviewed by the Clean Air Scientific Advisory Committee (CASAC) in April and August, 1982. This final product incorporates the suggestions and recommendations of the CASAC as well as other appropriate comments received on the initial drafts. The CASAC closure letter on the staff paper (Goldstein, 1983) is reproduced in Appendix E.

III. APPROACH

The approach used in this paper is to assess and integrate information derived from the criteria review in the context of those critical elements which the staff believes should be considered in the review of the primary and secondary standards. Particular attention is drawn to those judgments that must be based on the careful interpretation of incomplete or uncertain evidence. In such instances, the paper states the staff's evaluation of the evidence as it relates to a specific judgment, sets forth appropriate alternatives that should be considered, and recommends a course of action.

Sections IV and V review and integrate important scientific and technical information relevant to standard-setting. Because sulfur oxides are often studied in combination with particulate matter, much of the more important literature has already been assessed in the companion staff paper on particulate matter (EPA, 1982b). Where possible, pertinent references are made to the appendices of that paper with only summaries in the main body of this paper. Section IV presents relevant features of historical and current U.S. air quality to support discussions of both primary and secondary standards. Section V addresses the essential elements with regard to the primary standards; these include the following:

1) identification of possible mechanisms of toxicity;
2) description of effects and judgments of critical effects of concern for standard-setting;
3) identification of most sensitive population groups; and
4) discussion of controlled human and community studies relating level(s) and duration(s) of exposure to indicators of health effects.

Drawing from the discussion in Sections IV and V, Section VI identifies and assesses the factors the staff believes should be considered in selecting averaging times, form, and level of primary standards. Preliminary staff recommendations on alternative policy options in each of these areas are also presented.

Section VII examines information in the criteria document the staff believes is most relevant with respect to secondary standards and focuses on the direct effects of SO_2 on vegetation, man-made materials, and personal comfort and well-being. Indirect effects on visibility and climate and acid deposition are not discussed. The elements addressed include:

1) description of effects and judgment of the critical effects of concern for standard-setting;

2) identification of causal mechanisms;
3) studies relating level(s) and duration(s) of exposure to indicators of effects; and
4) factors to be considered in selecting averaging times, form, and level of secondary standards.

Preliminary staff recommendations on policy options for secondary standards are also presented.

The principal focus of this paper is on the effects of SO_2, alone and in combination with other pollutants. Other sulfur oxide vapors (e.g., SO_3) are not commonly found in the atmosphere. The effects of the principal atmospheric transformation products of SO_2 (i.e., sulfuric acid and sulfates) are discussed in the companion staff paper on particulate matter.

IV. AIR QUALITY CONSIDERATIONS

This section summarizes the relevant chemical and physical properties of SO_2 as it occurs in the ambient atmosphere and briefly characterizes ambient SO_2 levels to provide perspective for subsequent interpretation of health and welfare studies. More detailed discussion of these areas is contained in Chapters 2 and 5 of the criteria document ("CD", EPA, 1982a); supplemental analyses of air quality relationships are also outlined in Appendix D.

A. Chemical and Physical Characteristics

SO_2 is a rapidly diffusing reactive gas that is quite soluble in water, readily dissolving to form sulfurous acid ($H_2O \cdot SO_2$), a weak acid that dissociates into hydrogen (H^+), sulfite ($SO_3^=$), and bisulfite (HSO_3^-) ions. The solubility of SO_2 and the ratio of sulfite to bisulfite ions in aqueous solution increase significantly with increasing pH (and local ammonia concentration). The sulfite/bisulfite ratio is about 1:1000 at a pH of 7.4 (as in some body fluids) (CD, Figure 2-3). Total dissolved SO_2 increases by a factor of about 10^4 from pH 3 to pH 7.

SO_2 occurs in the ambient air with a variety of particles and other gases. The potential chemical and physical interactions among these numerous substances are complex and incompletely characterized (CD, pp. 2-62 to 2-69). The following generalizations are of some significance in evaluating the health and welfare effects of SO_2 in complex mixtures:

1) SO_2 is oxidized by a number of homogenous (gas-phase) and heterogeneous (liquid or solid surface phase) mechanisms to form sulfuric acid and, ultimately, other sulfates. SO_2 may also reversibly dissolve in or attach to particles or may form stable sulfite complexes (CD, pp. 2-38 to 2-40).

2) At low relative humidities, ambient SO_2 may adsorb onto the surfaces of dry particulate matter, but the extent of adsorbtion is limited by the available particle surface area. Because fine mode (< 2.5 µm) aerosols usually contain most of the available surface area, adsorbed SO_2 would most likely be found in the fine mode (CD, p. 2-71). Except in the case of particles of unusually high surface/mass ratios, or in the presence of pollutants promoting oxidation to sulfate, the amount of SO_2 adsorbed onto dry particles may be only a small fraction of total fine particle mass (Schryer et al., 1980).

3) At higher relative humidities, SO_2 will dissolve into available droplet aerosol. SO_2 solubility in such droplets is greater with lower temperature and lower droplet acidity (e.g., with elevated ammonia levels). Unless converted to sulfates, the SO_2 may be released from the droplet when it encounters lower gas phase SO_2 concentrations. At low ambient ammonia levels (< 1 part per billion [ppb]), the ultimate capacity for droplet absorption of SO_2 is limited to < 1% of droplet mass (Larson et al., 1978; Scott and Hobbs, 1967). Because of their low pH, little interaction would be expected between various ammonium sulfate or sulfuric acid aerosols and SO_2.

B. Ambient Concentrations

SO_2 concentrations can be examined on three geographical scales: 1) the vicinity (< 20 km) of major point sources, 2) urban areas, and 3) multi-county to multi-state regions. As indicated by the criteria document (CD, Chapter 5), SO_2 levels in urban areas and near many point sources have been markedly reduced by control programs over the past 10 to 15 years. Current (1979-80) SO_2 air quality data for approximately 900 population- and source-oriented sites with continuous monitors are summarized in Tables 4-1 and 4-2. These sites reflect a more limited number of counties and urban areas (approximately 500 total counties) with multiple SO_2 monitors. Annual SO_2 levels are less than 0.03 ppm (80 $\mu g/m^3$) in 99% of both site categories. Although the distribution of annual averages are similar in population- and source-oriented sites, short-term concentrations ($\leq$ 24 hours) tend to be higher at source oriented sites. Less than 5% of population-oriented sites had second maximum 24-hour levels in excess of 0.14 ppm (370 $\mu g/m^3$); over 5% of 24-hour second maxima at source-oriented sites exceeded this value. Similarily, less than 1% of population-oriented sites had second maximum 3-hour averages in excess of 0.5 ppm, while over 5% of second 3-hour maxima at source-oriented sites exceeded 0.5 ppm.

Tables 4-1 and 4-2 also contain two methods of displaying the 1-hour average SO_2 concentrations observed during 1979-80 at these sites. The first method consists of determining the distribution of maximum and second highest 1-hour average concentrations. This distribution corresponds with similar distributions at source- and population-oriented sites for 24-hour and 3-hour averages. The second approach gives the frequency distribution of the 99th percentile of all hourly SO_2 values at these sites.

As indicated in the tables, in 50% of the sites, the annual maximum 1-hour SO_2 concentration would not exceed 0.16 ppm (population-oriented) to 0.32 ppm (source-oriented). Maximum hourly levels at sites with the highest concentrations can reach substantial values (0.7-2.3 ppm), but such levels occur less than 1% of the time for 99% of all sites.

TABLE 4-1a. CHARACTERIZATION OF SO_2 LEVELS (IN PPM) AT POPULATION-ORIENTED MONITORING SITES FOR DIFFERENT AVERAGING TIMES*

Distribution of the Summary Statistic	Annual Average	24-Hour Average		3-Hour Average		1-Hour Average		
		Maximum	Second Maximum	Maximum	Second Maximum	Maximum	Second Maximum	99th Percentile
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50th Percentile	0.01	0.06	0.05	0.12	0.11	0.16	0.14	0.06
95th Percentile	0.02	0.14	0.11	0.34	0.28	0.45	0.38	0.13
99th Percentile	0.03	0.21	0.14	0.45	0.40	0.70	0.53	0.20

*Source: 1979-1980 SAROAD data base, 24- and 3-hour averages derived from running averages. Based on 761 site-years at 521 sites.

TABLE 4-1b. APPROXIMATE CONVERSION OF PPM TO $\mu g/m^3$ FOR SO_2

PPM	Approximate $\mu g/m^3$
0.01	25
0.02	50
0.03	80
0.04	100
0.05	130
0.1	260
0.5	1300
0.75	2000
1.0	2600

TABLE 4-2. CHARACTERIZATION OF SO_2 LEVELS (IN PPM) AT SOURCE-ORIENTED MONITORING SITES FOR DIFFERENT AVERAGING TIMES*

Distribution of the Summary Statistic	Annual Average	24-Hour Average		3-Hour Average		1-Hour Average		
		Maximum	Second Maximum	Maximum	Second Maximum	Maximum	Second Maximum	99th Percentile
Minimum	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00
50th Percentile	0.01	0.07	0.06	0.22	0.18	0.32	0.27	0.08
95 Percentile	0.02	0.23	0.18	0.77	0.58	1.33	1.00	0.27
99 percentile	0.03	0.41	0.28	1.36	1.13	2.30	1.62	0.49

*Source: 1979-1980 SAROAD data base, 24-and 3-hour averages derived from running averages. Based on 581 site-years at 364 sites.

The typical diurnal behavior of SO_2 is shown in Figure 4-1, which represents a frequency distribution of maximum hourly SO_2 concentrations at sites that are with levels among the nation's highest (Frank et al., 1981). Maximum SO_2 levels most frequently occur in the late morning to early afternoon during all seasons; this may be of some interest in evaluating exposures for both humans and vegetation. The pattern is consistent with elevated emission releases characteristic of major SO_2 emitters in combination with the diurnal variance in atmospheric turbulence. Substantial variance from this typical pattern can occur for sites involving complex terrain, marked diurnal emissions trends, or other exceptional atmospheric flows and source operating characteristics (Frank et al., 1981). On a seasonal basis, monthly average SO_2 levels tend to be higher in winter months in those areas affected by SO_2 emissions from space heating, but like diurnal patterns, seasonal variation is dependent on site-specific source, terrain, and meteorological characteristics (CD, p. 5-18).

Although non-urban levels of SO_2 are substantially lower than those found in urban or source oriented sites, in some areas SO_2 levels appear clearly in excess of those expected in most natural settings (< 0.004 ppm, CD, p. 5-5). Data from the 54 station non-urban SURE network indicate that SO_2 concentrations, like those of its transformation products (sulfates), are elevated on a regional scale in large portions of the northeastern U.S. (Figure 4-2). If the data from this network are representative, ground level SO_2 concentrations in large portions of the northeast (0.01-0.02 ppm, or 25-50 $\mu g/m^3$) are substantially higher than sulfate levels in the same region (6-12 $\mu g/m^3$), on both a chemical equivalent and mass concentration basis (Mueller et al., 1980). As

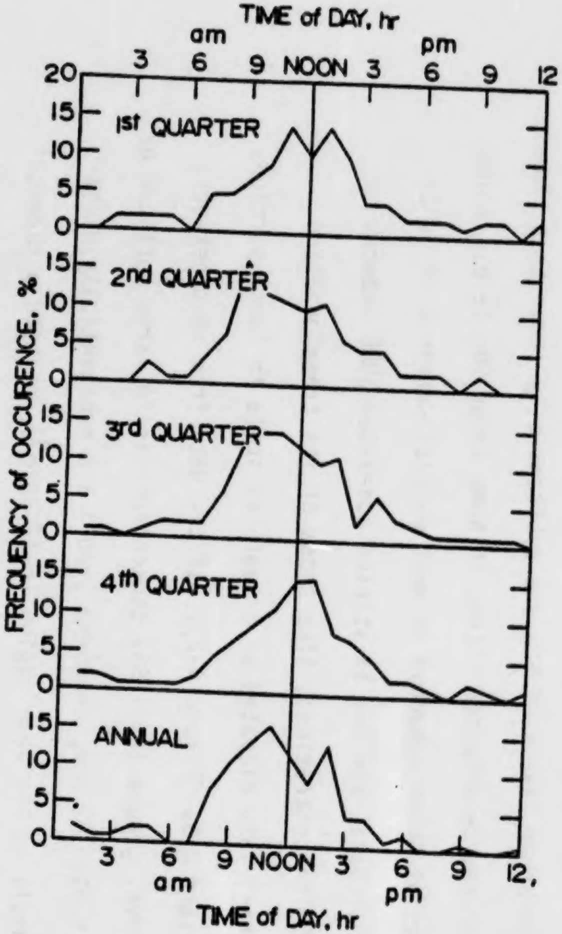

Figure 4-1. Distribution of the typical hour of maximum SO_2 among 153 monitoring locations, 1975-1978 (Frank et al., 1981). Sites from EPA National Air Data Bank include all those with $\geq$6000 hourly observations/year with annual average for at least 1 hour $\geq$0.03 ppm SO_2.

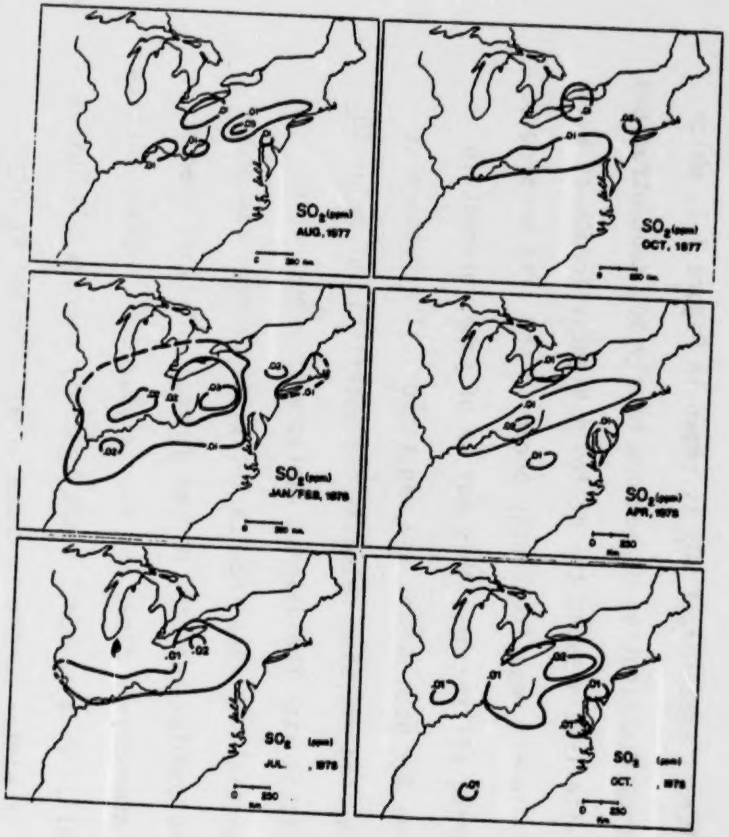
SO2 (ppm) AUG. 1977
SO2 (ppm) OCT. 1977
SO2 (ppm) JAN/FEB. 1978
SO2 (ppm) APR. 1978
SO2 (ppm) JUL. 1978
SO2 (ppm) OCT. 1978
.01
.02
.03
0 250 km

Figure 4-2. Monthly Arithmetic Mean Sulfur Dioxide Concentrations at Nonurban Sites in the Northeast (Mueller et al., 1980).

evidenced by the same network, non-urban average and peak ozone levels were also elevated in this region. Unlike SO_2, which on a regional scale is highest in winter months, both ozone and sulfates tend to have summer maxima.

V. CRITICAL ELEMENTS IN THE REVIEW OF THE PRIMARY STANDARD

A. Mechanisms

This section discusses the factors that influence deposition and clearance of SO_2 in the respiratory tract and outlines the mechanisms by which SO_2, alone and in combination with other factors, may initiate physiological and pathological responses. This discussion is intended to aid interpretation of the role of SO_2 in producing responses observed in humans.

1. Deposition and Clearance

An evaluation of the mechanisms by which SO_2, alone and in combination with particles, may affect human health must recognize the importance of deposition and clearance of SO_2 in the major regions of the respiratory tract. As described in the criteria document, the respiratory tract can be classified according to three major regions: 1) extrathoracic, including the passages of the nose, mouth, nasal pharynx, oral pharynx, epiglottis, and larynx, 2) tracheobronchial, including the ciliated airways from the trachea to the terminal bronchioles, and 3) alveolar or pulmonary, including the respiratory bronchioles, alveolar ducts and sacs, atria, and alveoli (CD, p. 1-52).

Due to its high solubility in aqueous solutions of near neutral acidity (e.g., physiological fluids), SO_2 is readily absorbed upon contact with the moist surfaces of the nose and other upper respiratory passages (CD, p. 1-54). Deposition of SO_2 in the airways of the upper extrathoracic region determines how much SO_2 is available for penetration to the more sensitive larynx and the tracheobronchial and alveolar regions. SO_2 (1 to 50 ppm) is almost completely absorbed ($\geq$ 99%) by nasal removal under resting conditions in both man and laboratory animals (Frank et al., 1969; Speizer and Frank, 1966b; Brain, 1970). No evidence for decreased nasal removal was found even after six hours at 25 ppm (Andersen et al., 1974).

Factors that can increase penetration and deposition of SO_2 in the respiratory tract over that observed for quiescent nasal breathing include mouth and oronasal breathing, increased ventilation rates, and the presence of airborne particles that may act as "carriers" for SO_2. These factors, critical in the interpretation of studies of the health effects of SO_2, are summarized briefly in Appendix A.

Although most inspired SO_2 appears to be readily absorbed into moist upper respiratory tract surfaces, about 15 and 30% of inhaled SO_2 is expired in resting human subjects for nose and mouth (only) breathing, respectively (Melville, 1970). The results of Speizer and Frank (1966b) suggest that the expiration may be the result of partial desorption of inhaled SO_2. Absorbed SO_2 is rapidly transferred into the circulatory system from all regions of the respiratory tract, a small fraction of which may be desorbed into the alveolar region from the blood (Frank et al., 1967).

In body fluids, SO_2 rapidly forms a solution of bisulfite and (in smaller quantities) sulfite. Animal and in vitro studies indicate that these substances can reversibly react with compounds containing disulfide linkages (e.g., proteins) to form S-sulfonate (sulfonation reaction) (Guunnison and Palmes, 1973). The predominant metabolic fate of the sulfur/sulfonate complex appears to be oxidation to sulfate as mediated by the enzyme sulfite oxidase and excretion in urine (Gunnison and Palmes, 1973; Yokoyama et al., 1971).

2. Mechanisms of Toxicity

SO_2 may produce physiological and, ultimately, pathological effects by mechanisms that depend upon amount and site of deposition, reactions with biological materials, and sensitivity of the affected region. The major mechanisms of potential interest in SO_2 toxicity are discussed in Appendix A. They can be briefly categorized as follows:

a) irritation of tissues or nerve receptors leading to airway/functional changes;

b) alteration of clearance and other host defense mechanisms;

c) tissue irritation or damage leading to morphological alterations; and

d) reactions with important cellular constituents.

B. Effects of Concern

This section identifies and describes the principal effects that may be associated with SO_2, alone and in combination with other pollutants. Evidence for such associations is drawn from animal toxicology, controlled human exposure and community epidemiological studies.* Based on these data, as summarized in the criteria document, the following effect areas appear to be of most interest:

1) sensory and other non-respiratory responses;
2) respiratory mechanics and symptoms;
3) aggravation of existing respiratory and cardiovascular disease;
4) clearance and other host defense mechanisms;

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*Frequent reference is made to previous staff evaluations of these data as presented in Appendix B of the companion staff paper on particulate matter (EPA, 1982b).

5) potential mutagenesis/carcinogenesis; and

6) mortality.

The major implications of the available literature related to each of these effects areas are summarized below.

1. Sensory and Other Non-Respiratory Responses

Sensory and certain other non-respiratory responses to sulfur oxides have been studied in controlled human exposures. In Soviet tests, the average odor threshold for SO_2 was 0.8 to 1 ppm (Dubrovskaya, 1957). In controlled U.S. tests, the odor threshold was 0.47 ppm (A.D. Little, Inc. 1968). Under more typical conditions, most individuals would probably be less responsive to such levels (CD, p. 13-5). The sensitivity of the eye to light during dark and light adaptation is increased by short-term SO_2 exposures as low as 0.23 to 0.34 ppm (Dubrovskaya, 1957; Shalamberidze, 1967). Electroencephalographic measurements of alpha rhythms show an interruption of these brain waves at 20-second SO_2 exposures of 0.3 to 1 ppm (Bushtueva, 1962).

These effects of sulfur oxides have no known implications for health, and near these threshold levels bear little obvious relation to personal comfort and well-being. Given the odor thresholds, it is possible that subjects might detect the presence of SO_2 at levels on the order of 1 ppm SO_2 in controlled human studies involving nose breathing, making truly double blind experiments difficult.

2. Respiratory Mechanics and Symptoms

Effects on respiratory mechanics can range from mild transient changes of little apparent direct health consequence to incapacitating impairment of breathing. Symptomatic effects also vary in severity, but at minimum, indicate a biological response.

a) SO$_2$ Alone

Few animal studies have evaluated the acute effects of SO$_2$ exposure on pulmonary mechanics (CD, Table 12-3). The most sensitive species tested is the guinea pig; the lowest 1-hour exposure to produce an increase in flow resistance in any animals tested was 0.16 ppm (Amdur and Underhill, 1970). Sensitivity varies with experiment and later studies in the same laboratory found no responses at higher levels (0.2 to 0.8 ppm) (Amdur et al., 1978b). The collective experience of guinea pig exposures to SO$_2$ alone suggests the following:

1) Response of individual animals varies widely, with on the order of 10% of animals tested from 1964-1974 considered as "susceptible" (Amdur, 1964, 1973, 1974).
2) Negative findings below 1 ppm in later years may be due to differences in strains of animals (CD, pp. 12-15 to 12-16).
3) The time course of guinea pig response (response increased with exposure, slow to recover) appears different from the short-term responses seen in resting humans and cats and dogs (Corn et al., 1972; Frank and Speizer, 1965; Nadel et al., 1965).
4) The lowest level at which response occurs is substantially below those seen for other animals and humans where exposure was also through predominantly quiescent nasal breathing.
5) Exposure conditions (intrapleural catheter, restraints, nasal breathing, effects of prior anesthesia) may increase or otherwise alter response (NAS, 1978, p. 7-14).

In essence, it is clear that the guinea pig results should be interpreted cautiously when drawing qualitative conclusions with respect to effects in humans.

A number of controlled human exposure studies have examined the acute effects of SO_2, alone and in combination with other pollutants, on respiratory function and on subjective symptoms indicating discomfort. The more important findings of a collection of such studies are summarized in Table 5-1. The studies vary in a number of characteristics (e.g., exposure mode, exercise levels) that are important when considering more quantitative observations than are intended in this section. These as well as other studies of interest are more fully discussed in Chapter 13 of the criteria document and in Appendix B of this paper. Those most useful for quantitative conclusions are also discussed in Section V-D of this paper.

Key conclusions with respect to the effects of SO_2 derived from the evaluation in Appendix B include:

1) The major observed response to short-term exposures to SO_2 appears to be bronchoconstriction, usually evidenced in increased airway resistance and decreased expiratory flow rates. Asthmatics, and to a lesser extent, atopic individuals with allergic responses but no clinical manifestations of asthma, are substantially more sensitive to these effects. Significant increases in airway resistance and occurrence of symptoms such as shortness of breath and wheezing have occurred in short-term mouthpiece, face mask and/or free breathing exposures to 0.5 to 0.75 ppm SO_2 with moderate exercise (Sheppard et al., 1981a; Kirkpatrick et al., 1982; Linn et al., 1982a,b), but not at rest or with light exercise (Sheppard et al., 1981a; Linn et al., 1982a).
2) The time course of SO_2 induced reflex bronchoconstriction varies with exercise, method, and duration of exposure, and subject

TABLE 5-1. EFFECTS OF SO_2 ON RESPIRATORY MECHANICS AND SYMPTOMS

Exposure	Observations*	References
Healthy Subjects		
5 ppm SO_2, 3-180 minutes, mostly resting, various routes	Most studies report changes in function measurements, bronchoconstriction. Increased symptoms: throat irritation and dryness, cough.	Amdur et al. (1953); Andersen et al. (1974); Frank et al. (1962); Kreisman et al. (1976); Lawther et al. (1975); Melville (1970); Nadel et al. (1965); Newhouse et al. (1978); Sheppard et al. (1980); Sim and Pattle (1957); Snell and Luchsinger (1969); Tomono (1961)
1-4 ppm SO_2, 3-30 minutes, mostly resting, various routes	Mixed results; some subjects appear more sensitive; some changes in function measurements indicating bronchoconstriction (e.g., increased airway resistance, decreased MEFR, MMFR); some subjects report symptoms such as throat irritation; usually greater response with oral breathing, exercise.	Amdur et al. (1953); Burton et al. (1969); Frank et al. (1962); Kreisman et al. (1976); Lawther et al. (1975); Melville (1970); Nadel et al. (1965); Sim and Pattle (1957); Sheppard et al. (1980); Snell and Luchsinger (1969); Tomono (1961); Koenig et al. (1982b)
0.37-0.75 ppm SO_2, 15-180 minutes, various routes, activities	5 studies - No effects on function, symptoms, equal to or less than 0.5 ppm SO_2. 2 studies - Decrease in MEFR, FVC, $FEV_{1.0}$, MMFR at 0.75 ppm, free breathing with moderate to heavy exercise.	Bates and Hazucha (1973); Bedi et al. (1979); Bell et al. (1977); Horvath and Folinsbee (1977); Jaeger et al. (1979); Snell and Luchsinger (1969); Stacy et al. (1981)
Atopic Subjects		
1 ppm SO_2, with and without 1 mg/m^3 NaCl (0.9 μm) droplets. Rest and exercise, 10 to 40 minutes	At rest, 1 of 7 subjects had increased airway resistance. With exercise, decreased flow and other parameters suggesting effects in central and small airways. No difference between SO_2 + NaCl, SO_2 alone.	Sheppard et al. (1981a); Koenig et al. (1982a)
Asthmatic Subjects		
1-5 ppm SO_2, 5-150 minutes, mostly at rest, oral exposures	Marked changes in respiratory function in most subjects (airway resistance, others). Numbers reporting wheezing, shortness of breath, dyspnea increase with dose, exercise; some require medication.	Sheppard et al. (1980); Sheppard et al. (1981a); Kirkpatrick et al., (1982)
1 ppm SO_2 + 1 mg/m^3 NaCl (0.9 μm)^2 droplets, RH 75%, oral, rest and exercise, 40-60 minutes	Decreased flow, other parameters suggesting effects in central and small airways; with exercise 5 of 8 experienced wheezing, 3 of 8 shortness of breath.	Koenig et al. (1980, 1981)
0.25 to 0.75 ppm SO_2, 5-60 minutes, light to moderate exercise, free breathing (chamber or face mask)	No effect at 0.25 ppm. At 0.5 ppm, no response at lowest exercise rate; with higher exercise, oronasal (face mask) exposure resulted in increased airway resistance in all subjects, symptoms in 4 of 6. At 0.75 ppm and moderate exercise, chamber exposure resulted in significant increase in both symptoms and airway resistance; functional effects less than those for similar mouthpiece exposures.	Linn et al. (1982a,b); Kirkpatrick et al. (1982)
0.1-0.5 ppm SO_2, 5-180 minutes, various activity levels, oral exposures	Incremental increases in airway resistance in some subjects at all levels, slight change in MMFR, resting subjects; wheezing, shortness of breath in some subjects; potentiated by exercise.	Jaeger et al. (1979); Sheppard et al. (1981a); Linn et al. (1982a); Kirkpatrick et al. (1982)

*Lung function tests listed here are briefly described in Appendix C.

sensitivity. In normal resting subjects, maximal response is rapid (5-10 minutes) and decreases quickly following exposures. Recovery may be delayed after exercise and appears longer for sensitive asthmatics and subjects with apparent bronchial obstruction (Sheppard et al., 1981a; Gökemeijer et al., 1973).

3) Preliminary evidence suggests SO_2 may increase sensitivity to subsequent challenge by other bronchoconstrictors (Islam et al., 1972; Reichel, 1972). This might explain the as yet unreplicated finding of delayed symptomatic response following SO_2 exposure (Jaeger et al., 1979).

4) A gradual rise in SO_2 exposure appears less likely to result in reflex bronchoconstriction than a rapid "step function" increase (Andersen et al., 1974; Schachter, 1982). In the ambient environment, such an increase might occur by moving from indoors to outdoors or by a meandering source plume. Because the response is probably more dependent on dose at sensitive receptors than on ambient SO_2 levels, the onset of exercise may also produce a "step function" increase in "effective" SO_2 levels at these receptors; this is evidenced by the marked increase in airway resistance following exercise, even in subjects who were just previously exposed to the same level at rest for 30 minutes at levels (0.5 or 0.75 ppm) that did not produce functional changes (e.g., Stacy et al., 1981; Koenig et al., 1982a).

5) Longer-term studies (6 hours to 6 days) have found no effects of continuous exposure to 0.3 ppm SO_2 in apparently resting normal subjects or subjects with prior airway impairment but provide some evidence of changes in nasal cross-sectional area and pulmonary

function changes at 1 ppm (Andersen et al., 1974; Weir and Bromberg, 1972). Suggestion of a progressive decrease in functions was observed at 3 ppm. In these extended studies, impaired or bronchitic subjects did not appear more sensitive than normals, but this is confounded by large day-to-day variation in baseline lung function (Weir and Bromberg, 1972) or use of medication and incomplete reporting of techniques (Reichel, 1972).

6) Chronic animal studies provide no evidence supporting concern over direct SO_2 effects on respiratory mechanics of long-term average exposures to even high ambient levels (CD, Table 12-3). Repeated peak exposures, however, have not been properly assessed.

7) Although particles may potentiate the effect of SO_2 by increased penetration or chemical reaction, controlled human exposures have found mixed results, with little convincing evidence that such enhancement occurs for laboratory aerosol conditions at realistic peak aerosol levels (Appendix B). Ambient conditions that might tend to maximize interactions between SO_2 and particles (cold temperatures, fog droplets, substantial NO_2, NH_3) have not been systematically examined in the laboratory.

8) Combinations of SO_2 and other atmospheric gases (principally O_3) have also produced mixed results. One study (Bates and Hazucha, 1973) reported marked synergism for SO_2 plus O_3, both at 0.37 ppm, but follow-up work in several laboratories failed to confirm the initial findings. The weight of evidence suggests some reason for caution with respect to mixtures of SO_2, O_3, and sulfates, but the issue is unresolved (CD, p. 13-52).

9) A number of long-term community air pollution studies (Table B-3, EPA, 1982b) have found that populations living in areas with high SO_2 and particles tend to have a higher prevalence of respiratory symptoms and lower lung functions than those living in areas with lower pollution levels. The data do not, however, permit clear identification of the importance of SO_2 in the pollution mix. Some cross-sectional (Neri et al., 1975; Becklake et al., 1978) and longitudinal studies (Van der Lende, 1973, 1975, 1981) provide weak qualitative evidence of effects associated with differences in SO_2 levels, although in the presence of particles.

Two series of studies (Lawther et al., 1974a,b,c; Dockery et al., 1981) provide qualitative evidence of lung function decrements in adults and children in response to episodic increases in SO_2 levels in combination with particles.

3. Aggravation of Existing Respiratory and Cardiovascular Disease

SO_2 induced bronchoconstriction or other acute responses described above clearly aggravate asthmatics in laboratory situations and might also aggravate those with other respiratory ailments and cardiovascular disease. A number of community observational studies (Table B-4, EPA, 1982b) of episodic as well as more moderate acute exposures to high levels of SO_2 in combination with particulate matter qualitatively suggest that these exposures aggravate the conditions of cardiovascular patients and individuals with bronchitis, emphysema, pneumonia, and influenza. The relative importance of SO_2 in these pollutant exposures is difficult to specify.

Epidemiological support for aggravation of asthma by SO_2 is weak (CD, p. 14-34). In addition to the usual problems associated with community epidemiological studies (CD, Section 14.1), studies of asthmatics are confounded by limited numbers of subjects, use of medication, and multiple stimuli other than air pollution that may affect response. In addition, no studies have measured short-term ($\leq$ 1 hr) peak levels most likely to be responsible for any effects. Because 1-hour maxima tend to be highest in the vicinity of strong point sources, the study of asthmatics by Cohen et al. (1972) conducted near a coal-fired power plant is of most direct relevance to the controlled human results. Although the results do suggest an SO_2 (and particulate matter) effect on the frequency of attacks, potential biases and other methodological difficulties with the study (CD, p. 14-33) and the lack of 1-hour SO_2 data make unequivocal conclusions impossible.

4. Clearance and Other Host Defense Mechanisms

Major host defense mechanisms potentially affected by SO_2 include clearance of particles and other foreign matter from the respiratory tract and other respiratory system related defenses against infectious agents.

Few controlled human studies have examined the effects of SO_2 on clearance. Extended nasal exposure (4 to 6 hours) to 5 and 25 ppm SO_2, alone and in combination with (2 or 10 mg/m^3) "inert" particles, significantly reduced nasal mucous flow rates in resting healthy adult subjects (Andersen et al., 1974, 1977, 1981). The effects of particles were additive at most. Mucous flow was also reduced at 1 ppm SO_2, but not significantly so (Andersen et al., 1974). An interesting observation in the earlier study was an abnormally high (4 of 15) incidence of colds within one week of SO_2 exposures of 1, 5, and 25 ppm on successive days. The evidence did not relate this increase to SO_2

exposures. This anecdotal result prompted a follow-up study (Andersen et al., 1977) in which SO_2 exposed and control groups were subjected to experimentally induced rhinovirus infection. The SO_2 exposed group had no increase in the number of colds and had fewer symptoms. The significance of this finding with regard to cold incidence is made questionable by the fact that virus was innoculated into a region of the nose previously known not to be affected by SO_2 induced reduction in clearance. The innoculated region is out of the mainstream sites of deposition for both airborne virus and SO_2 (Andersen et al., 1977). A related anecdotal result of interest is the observation of Weir and Bromberg (1972) that recovery from mild upper respiratory infections was slower for subjects exposed to 5 ppm SO_2 for several days than for control subjects. Statistical evaluation was not possible due to the small number of subjects.

Wolff et al. (1975a,b) and Newhouse et al. (1978) have examined the effects of single acute exposures to SO_2 on tracheobronchial mucociliary clearance. At 5 ppm, SO_2 produced only a transient acceleration in tracheobronchial clearance in normal, healthy subjects for oral, resting exposures of 1 to 2 hours. Significantly increased clearance was found for a 2.5 to 3 hour exposure that included a 30 minute exercise period. Exercise alone increased clearance but the rate for those undergoing exercise and SO_2 was significantly faster. Unfortunately, no published studies have examined SO_2 induced effects on clearance in sensitive subjects or the effects of repeated peak exposures in humans.

Animal studies have examined the effects of both short- and long-term SO_2 exposures on clearance and other host defense mechanisms (CD, Table 12-4). Unlike the animal-human comparisons observed for sulfuric acid (e.g., Leikauf et al., 1981), donkeys appear far less sensitive to acute SO_2 exposures than are humans, with no response at 25 ppm (Spiegelman et al., 1968). Rats may be more sensitive (Ferin and Leach, 1973). Of particular interest is the finding that prolonged, repeated exposures (1.5 to 7 hours/day) to relatively low levels may result in clearance effects (Ferin and Leach, 1973; Hirsch et al., 1975). Ferin and Leach (1973) exposed rats to 0.1, 1 or 20 ppm SO_2 for 7 hr/day, 5 days/wk for 10 and 25 days as an indicator of "integrated alveolar clearance." SO_2 at 0.1 ppm accelerated clearance at 10 and 23 days, but 1 ppm accelerated clearance at 10 days, had no significant effect at 18 to 20 days, and depressed clearance at 25 days. Twenty ppm depressed clearance after 11 days. The mechanisms by which SO_2 might affect apparent alveolar clearance is unclear, but would not appear to be related to penetration and direct effects on alveolar macrophages or cilia beat frequency (Fraser et al., 1968). Hirsch et al. (1975) found that tracheal mucous flow was slowed in beagles exposed to 1 ppm SO_2 for 1.5 hours twice a day, 5 days a week, for 1 year. Clearance was examined only once (24 hours after exposure) and not measured prior to exposure. Thus, the time to produce an effect is unclear, and the extent of the depression is called into question. In essence, the results of SO_2 on clearance suggest some concern over repeated peaks, but confirmatory testing is needed.

As discussed in Section V-A and Tables 12-4 and 12-13 of the criteria document, the effects of weekly to 3-month exposures to high levels of SO_2 appear to affect antiviral defenses but not susceptibility to bacterial infection. Some suggestion of effects of SO_2 and carbon on pulmonary immune responses exists (Zarkower, 1972) but their mechanisms were considered puzzling.

Community epidemiological studies (Holland and Reid, 1965; Lambert and Reid, 1970) of elevated SO_2 in combination with particles suggest that long-term exposures may be associated with an increase in the prevalence of bronchitis. Although the role of SO_2 versus sulfuric acid or other particles is not clear, animal studies suggesting effects of repeated SO_2 peaks on clearance provide some basis for SO_2 involvement. Community studies (Table B-7, EPA, 1982b) also suggest increased infectious disease during pollution episodes and in children and adults living in areas of higher SO_2/particle pollution. Again, the relative role of SO_2 in such responses is unclear.

5. Possible Mutagenesis/Carcinogenesis

SO_2 and bisulfite have been reported to be mutagenic in microbial test systems (CD, Table 12-15) at acidic pH. Potential mechanisms (e.g., reaction with nucleic acids, free radical production) are outlined in Appendix A. The relevance of the microbial results to whole animals is unclear. Negative results have been reported for mammalian cells and insects (CD, Table 12-15). The criteria document concludes that "On the basis of present evidence, one cannot decide whether or not bisulfite, and hence SO_2, is a mutagen in mammals" (CD, p. 12-77).

Two studies have examined the potential carcinogenicity of SO_2 alone. Lifetime exposures of rats to 10 ppm SO_2 for 6 hr/day produced no squamous cell carcinoma (Laskin et al., 1976). Peacock and Spence (1967) as reanalyzed by EPA (CD, Appendix, Chapter 12), found a significant increase in primary lung carcinoma in female mice and primary lung adenomas in male and female mice. Unfortunately, the data do not permit calculation of exposure level, which was in the nature of intermittent peaks (high concentration unspecified, 5 minutes, 5 days/wk) for 300 days. The combination of 10 mg/m^3 benzo(a)pyrene (BaP) and SO_2 produced no lung tumors in hamsters but a significant increase in lung carcinoma in rats (Laskin et al., 1970). A follow-up study in rats found that lifetime exposure to SO_2 (10 ppm, 6 hr/day) alone and BaP (10 mg/m^3, 1 hr/day) alone produced no significant change in tumors, but various combinations of SO_2 and BaP did result in increased lung tumors (Laskin et al., 1976). The criteria document concludes that it is difficult to interpret the studies of carcinogenicity, "However, SO_2 must remain suspect as a carcinogen or cocarcinogen in view of these reanalyses and the positive results of mutagenicity assays" (CD, p. 12-78).

Retrospective community epidemiological studies of cancer (Appendix B.5, EPA, 1982b) have focused on areas with high particles (especially BaP) pollution. Nevertheless, SO_2 levels were also high in most areas examined. In essence, most studies find that cigarette smoking is the dominant cause of lung cancer, but some small portion of the observed gradient in urban/rural cancer rates in smokers and non-smokers may have been related to high historical levels of community air pollution. Available studies neither prove nor negate the possibility that SO_2, alone or acting with particulate carcinogens, may have contributed to cancer.

6. Mortality

A number of epidemiological studies have demonstrated an association between peak SO_2 and particulate pollution and increased mortality rates (Table B-10, EPA, 1982b). Observations during the severe pollution episodes in Europe and the U.S. suggest that most of the pollution-related deaths were among the elderly and those with chronic cardiopulmonary disease.

Because of the high correlation between SO_2 and particle levels during these study periods, the relative importance of these pollutants are difficult to distinguish. The combination of elevated levels of SO_2 and particles with fog in the urban smog episodes likely resulted in increased penetration of SO_2 or its irritant transformation products. Whether SO_2, alone or in combination with particles, increased mortality during "episodic" as well as "non-episodic" conditions is unknown. Several analyses of daily mortality in London, New York City, and Pittsburgh suggest, however, that associations between air pollution and mortality are primarily due to particles and not SO_2 (Mazumdar et al., 1981; Schimmel and Murawski, 1976; Mazumdar and Sussman, 1981). Although these studies employed refined statistical techniques, the criteria document indicates that they cannot clearly separate the effects of SO_2 and particles nor rule out possible interactive effects between the pollutants, humidity, and other factors (CD, p. 14-53).

C. Sensitive Population Groups

This section identifies the major groups most likely to be among the most sensitive to the effects of SO_2, based principally on material presented in Sections A and B. Available estimates of the size of each of these groups in the U.S. population are also given. Table 5-2 draws upon information from epidemiological, toxicological, and controlled human research in summarizing the observations that have identified various subgroups and possible explanations for their sensitivity. Much individual variation exists among the subgroups.

TABLE 5-2. MAJOR SENSITIVE POPULATION SUBGROUPS*

Subgroup/ Disease Characteristics	Population Estimates	Rationale (or Criteria)	Observation/Associations Supporting Increased Sensitivity
Asthmatics - recurrent episodes of cough, wheezing, and breathlessness resulting from reversible airway obstruction caused by bronchial constriction, bronchial wall swelling, and accumulated secretions (NIAID, 1979)	9,300,000 (derived from prevalence estimate of NIAID, 1979 and applied to 1982 U.S. population)	- Hyperreactive airways (Boushey et al., 1980)	Exaggerated bronchoconstriction in asthmatics exposed briefly to SO_2. Effects at SO_2 levels up to an order of magnitude lower than in normal subjects (Sheppard et al., 1980, 1981a; Linn et al., 1982a,b; Koenig et al., 1982a). Longer recovery to normal lung function required in exercising asthmatics following brief SO_2 exposure (Sheppard et al., 1981a; Koenig et al., 1981).
Individuals with non-asthmatic atopic disorders, e.g., hay fever, other allergies - clinical hypersensitivity state, or allergy, to a variety of environmental antigens (NIAID, 1979)	20,000,000 (derived from prevalence estimates of Johnson, 1982b and applied to 1982 U.S. population)	- Hyperreactive airways (Boushey et al., 1980)	Increased bronchoconstriction after SO_2 in atopic individuals without asthma compared with normal subjects (Stacy et al., 1981; Koenig et al., 1982a; Sheppard et al., 1980) Numerous investigators have found individuals (10-20% of subjects) substantially more responsive to SO_2 than the rest of the group (CD, p. 13-20).
Individuals with chronic obstructive pulmonary diseases • Bronchitis - chronic inflammation of the trachea and bronchus with recurrent cough and sputum (Fishman, 1980) • Bronchiectasis - chronic dilatation of bronchi (Fishman, 1980) • Emphysema - unevenly distended lung airsacs, usually with loss of lung tissue (Fishman, 1980)	7,800,000 (DHEW, 1973)	- Mucus hypersecretion and blocked airways may worsen effects of SO_2-induced bronchospasm. - Enlarged airspaces increase blood flow resistance through the pulmonary capillary network, increasing cardiac stress.	Many of the deaths and illnesses during and after air pollution episodes were among people with pre-existing obstructive diseases (Martin, 1964; Martin and Bradley, 1960; Ministry of Health, 1954; Lawther et al., 1970). Longer recovery to normal lung function required in bronchitics following brief SO_2 exposure (Gokemeijer et al., 1973).

*Other identifiable groups that may have enhanced sensitivity to SO_2 include individuals with cardiovascular disease, the elderly, and children and adolescents (see text).

Moreover, some of these groups may be at lower risks, as in the case of patients confined to indoor environments with lower than ambient SO_2 levels.

Asthmatics are substantially more sensitive to a brief exposure to SO_2 than are normal subjects. Table 5-3 provides a quantitative comparison of the relative sensitivity to SO_2 of asthmatics, atopics, and normal individuals as indicated by pulmonary function tests. Asthma is a common disease that affects approximately 9.3 million people in the U.S. (NIAID, 1979), although higher estimates have been made (Dodge and Burrows, 1981).

Increased sensitivity to SO_2, less marked than in asthmatics (Table 5-3), has also been noted among atopic individuals without any clinical signs of asthma (Koenig et al., 1982a; Stacy et al., 1981; Sheppard et al., 1980). Koenig et al. (1982a) suggest that hyperreactive atopics with exercise induced bronchospasm (EIB), who, in one study, made up about 41% of the allergic persons under age 18 (Kawabori et al., 1976), should perhaps be categorized as having subclinical asthma. The undetected presence of asymptomatic atopics in studies of presumed "normal" subjects may account for the recurrent finding of subjects "hyperreactive" to SO_2 who generally make up 10-20% of the study group (CD, p. 13-20). A similar incidence of susceptible individuals has been observed in animal studies (CD, pp. 12-15 to 12-16). Temporary but marked airway hyperreactivity occurs in otherwise normal subjects with viral respiratory infection (Boushey et al., 1980).

Other diseases, which may or may not be associated with asthma appear to be important factors in the predisposition of certain individuals to the harmful effects of high SO_2/particulate matter

TABLE 5-3. COMPARISON OF RESPONSES IN NORMALS, ATOPICS, AND ASTHMATICS TO SO_2

a) SO_2 Alone[1] (Sheppard et al., 1980; 1981a)

Concentration (ppm)	% Change in Specific Airway Resistance (SRaw)		
	Normals	Atopics	Asthmatics
5	18*	33*	126*
3	-3	1.5	76*
1	-4	2.5	25*
.5	NA	NA	~0

*Significantly different from baseline ($p < 0.05$). Asthmatics, but not atopics, are significantly different from normals.

[1] Adult subjects at rest. Oral-mouthpiece exposure, 10 minutes.

b) 1 ppm SO_2 + 1 mg/m^3 NaCl[1] (Koenig et al., 1982a)

Pulmonary Functional Value	Percent Change in Functional Value		
	Normals	Atopics with EIB	Extrinsic Asthmatics
R_T ($3H_z$)	3.0	41*	67*
V_{max50}	-8.0	-29*	-44*
V_{max75}	-7.0	-44*	-50*
$FEV_{1.0}$	-6.0	-18*	-23*
FRC	10	0.3	7.0

*Significantly different from baseline.

[1] Adolescent subjects, measurements made after 10 minutes of moderate exercise. Oral-mouthpiece exposure, 30 minutes at rest, followed by 5-7 minutes break, followed by 10 minutes exercise.

combinations. The history of catastrophic pollution episodes as well as the lesser episodes in London have clearly indicated that chronically ill individuals, especially those with cardiovascular and obstructive respiratory diseases, and the elderly, were more severely affected than the general population. Whether these groups would also be sensitive to SO_2 alone is not clear. Bronchitics are reported to be among the most sensitive to elevated SO_2 and particles (Lawther et al., 1970). In limited multi-day clinical tests however, subjects with minor and more serious obstructive disease were not clearly more sensitive to SO_2 than normals (Weir and Bromberg, 1972; Reichel, 1972). Subjects with obstructed airways (e.g., bronchitics) may, however, require a substantially longer recovery time to baseline function following brief exposure to SO_2 than normal subjects (Gökemeijer et al., 1973).

Children are generally more active outdoors and contain a somewhat higher percentage of asthmatics and atopics (NIAID, 1979). Enhanced sensitivity and prolonged effects have been noted among children exposed to high levels of ambient SO_2 and particulate pollution (Lebowitz et al., 1972; Douglas and Waller, 1966; Colley et al., 1973; Kiernan et al., 1976; Becklake et al., 1978), but the effects cannot be attributed to a single pollutant. Moderate episodes of SO_2 (with particles) have been associated with depression of lung function in children (Dockery et al., 1981).

Based on limited studies, about 15% of healthy young adults tested appear to be habitual "mouth", or oronasal breathers under the conditions of the tests (Saibene et al., 1978; Niinimaa et al., 1981). Because the subjects and test procedures used could have affected the results, extrapolation of this estimate to the general population, including sensitive subjects, is uncertain. Anyone, however, may temporarily shift to oronasal breathing during exercise, conversation, singing, or illness with related nasal congestion. The decreased nasal cross sectional area caused by high SO_2 levels (Andersen et al., 1974) might itself result in increased oronasal breathing. While all mouth breathers may not have comparable sensitivity to SO_2, mouth breathers in sensitive groups (e.g., asthmatics or atopics) are likely to be at greater risk of effect. Because allergic subjects often have nasal obstruction, the proportion of "mouth" breathers in such groups may be of equal or greater magnitude to that observed in healthy subjects.

People with sulfite oxidase enzyme deficiency who are unable to detoxify SO_2 and/or sulfite for subsequent excretion are very few in the U.S. (Cohen et al., 1973). Because the condition has serious clinical implications regardless of SO_2 exposure (Mudd et al., 1967; Irreverre et al., 1967; Shih et al., 1977) it may be irrelevant for present consideration. Other individuals with an intermediate enzyme deficiency (heterozygotes) may be at an increased risk, especially with chronic exposure to SO_2. Although intermediate levels of sulfite oxidase activity in the liver of humans has been reported (Shih et al., 1977) the frequency of the heterozygote gene is not known.

D. Concentration/Response Information

As outlined in Section B, responses to SO_2, alone or in combination with other pollutants have been examined in roughly three time scales: 1) peak exposures (minutes-hours), 2) short-term exposures (hours-days), and 3) long-term exposures (months-years). Although a number of animal, controlled human, and community studies provide important qualitative information on the range of possible responses to SO_2 on these time-scales, only a more limited set of controlled human and epidemiological studies are of principal interest in examining concentration-response relationships in humans. The following review summarizes those studies cited by the criteria document as providing the most reliable quantitative information as well as a few other studies that provide reasonable evidence of exposure-response relationships without allowing derivation of specific levels. A further assessment of these studies as applied to selecting alternative levels for air quality standards is presented in Section VI.

1. Peak Exposures

The best information on the effects of relatively brief (minutes-hours) peak exposures to SO_2 is derived from studies of exposure of humans under controlled laboratory conditions. The importance and limitations of controlled human exposure studies are discussed in Section 13.1 of the criteria document. Such studies can provide accurate measurement of responses, exposure levels and conditions for a single pollutant or simple combinations of pollutants, and produce useful concentration-response relationships for a variety of subjects. Important limitations include: 1) ethical considerations reduce the exposure regimes and types of sensitive subjects studied; 2) the number of subjects per test is limited; 3) repeated peak exposures and other longer-term exposures usually cannot be done; 4) only a small number of possible combinations of environmental variables and subject-related variables can be examined; 5) laboratory studies may induce physical or psychological artifacts; 6) to date, only a limited number of endpoints (usually respiratory mechanics and symptoms) have been measured; and, 7) functional measurements used vary from study to study, making quantitative comparisons difficult.

a) Normal Subjects (< 5 ppm)

Concentration-response information for SO_2 exposures of 1 to 5 ppm in resting healthy subjects is summarized in the criteria document and in Table 5-1. Both oral (mouthpiece) and nasal exposures have been studied. Although a few isolated cases of sensitivity to SO_2 have been found, it is not clear that such subjects are not atopic and or undiagnosed asthmatics. Accordingly, the criteria document concludes: "...available evidence points to 5.0 ppm (13.1 mg/m^3) as being the most probable lowest observed effect level for induction of bronchoconstriction effects in healthy adults exposed to SO_2 while at rest" (CD, p. 13-48).

Exercise and oral breathing increases fractional penetration and total dose of SO_2 (Section V.A.) and therefore results in effects at lower ambient concentrations. Based on the work of Lawther et al. (1975), Melville (1970), Snell and Luchsinger (1969), and Koenig et al. (1982b), the criteria document concludes that induction of pulmonary mechanical effects may occur at SO_2 concentrations $\geq$ 1 to 3 ppm in exercising healthy subjects. Most of these studies involved forced oral breathing, in some cases with light exercise.

Table 5-4 summarizes the results of a selected group of controlled human studies involving peak ($\leq$ 1 to 3 hours) exposures to SO_2 levels at or below 1.0 ppm. When comparing these results for quantitative purposes, it is important to note the sensitivity of the subjects (normal, atopic, asthmatic), the exposure mode (chamber, oral-mouthpiece and/or nose clip, oronasal, or nasal) and exercise status. Most of the studies involved a rather rapid (step function) increase in SO_2 exposure. The importance of each of these factors is discussed in the criteria document (CD, Chapters 11, 13) and in Section V-B and Appendix A of this paper. The comments column of the table provides some interpretation of the functional testing results, based upon the general nature of the tests as summarized in Appendix C and discussions in the criteria document (Section 13.6).

Studies involving exercising healthy adults and free breathing (chamber) exposures are summarized in Table 5-4. Bates and Hazucha (1973) found decreases in several parameters indicative of airway constriction with 0.75 ppm exposure of adults under intermittent light exercise (minute ventilation (V_e) ~ 25 l/min). Due to the limited number of subjects, group mean changes were not statistically significant and the results are preliminary. Stacy et al. (1981) used the same exposure regime but with a single exercise period of heavy exercise (V_e ~ 60 l/min) sufficient to induce oronasal breathing. Indications of large airway constriction were significant, with a trend toward changes in smaller airways. Responses were greater in subjects reacting positively to allergen skin tests, suggesting that some of these healthy subjects were atopic (but without asthma). The criteria document concludes that these studies provide weak evidence of SO_2-induced bronchospasm in free breathing exercising healthy normal individuals at levels of 0.75 ppm (CD, p. 13-49). As noted by the authors and by the criteria document (CD, p. 13-51), the relatively small (8-20%) reversible changes in functional parameters observed in these studies are not likely to be of any health significance in the normal healthy adults tested. The principal significance of these studies is to indicate levels and conditions at which comparable or more marked functional changes might be expected in more sensitive

TABLE 5-4. SELECTED CONTROLLED HUMAN STUDIES OF QUANTITATIVE INTEREST

Concentrations	Duration	Number/ Type Subjects	Exposure Mode	Exercise Status[1]	Observations[2]	Comments	Reference
Normal Subjects							
0.75 ppm	120 minutes	4 Healthy Adults	Chamber	Intermittent light exercise; Alternating 15 minute periods V_e ~ 25 l/min)	Trend toward decrease in MMFR (8-10%), $MEFR_{50\%}$ (20%), FVC, $FEV_{1.0}$ (8-10%) No change in CC.	Suggests possible constriction in large airways, constriction in intermediate to small airways as measured by MMFR but not in small airways as measured by CC. Effect increased through 1.5 hours. No health significance to normal subjects.	Bates and Hazucha (1973)
0.75 ppm	120 minutes	15 controls 16 healthy adult males	Chamber (oronasal)	15 minute exercise period. End of first hour V_e ~ 60 l/min	Significant increase in Raw, (mean ≈ 15%), trend toward decreased FEF_{50}, FEV/FVC; maximal after 1 hr. No change in other parameters, symptoms. Positive allergen skin test subjects more responsive.	Indicates large airway constriction, possible small airway constriction. Consistent with Bates and Hazucha findings. Effects not of health significance to normal subjects.	Stacy et al. (1981)
.37-.5 ppm	120 minutes	64 healthy, adults 5 studies	Chamber	Intermittent exercise V_e ~ 30 l/min	No pulmonary function effects, symptom results mixed.	Indicates no effects in large or small airways. No detectable health effects.	Horvath and Folinsbee, (1977); Bedi et al. (1979; 1982); Bates and Hazucha (1973); Bell et al. (1977)
Asthmatics and Atopics							
1 ppm	10 minutes	7 normals 7 atopics (seasonal rhinitis) 7 asthmatics	Oral-mouthpiece	Resting	No effects in normals; 1 atopic, 4 asthmatics had increased SRaw, group increase significant (~ 25%); two of 4 responding asthmatics had chest tightening, wheezing.	Indicates asthmatics are significantly more responsive than normals or atopics. Indicates constriction in large airways in four asthmatics, possibly in one atopic. Symptoms indicative of clinical significance in some asthmatics.	Sheppard et al. (1980)
1 ppm	5 minutes	6 asthmatics adults	Oral-mouthpiece	Exercise, V_e ~ 31 l/min and hyperventilation	Marked increase (mean > 300%) in SRaw in all subjects. Dyspnea and wheezing in all subjects. Time course of response differs from resting subjects.	Indicates marked large airway constriction in asthmatics, symptoms indicative of clinical significance.	Sheppard et al. (1981a)
1 ppm SO_2 +1 mg/m^3 NaCl droplet aerosol	60 minutes	9 Extrinsic asthmatics (adolescents)	Oral-facemask (no mouthpiece)	Resting	Significant decrease in $V_{max\,50\%}$, $V_{max\,75\%}$ (mean ≈ 8-14%) after 30 minutes. No significant change in R_T, FRC, $FEV_{1.0}$. No symptoms.	Indicates minimal constriction in small airways, no clear large airway constriction. Effect of aerosol not clear in this study.	Koenig et al. (1980)
1 ppm SO_2 + 1 mg/m^3 NaCl droplet aerosol	30 minutes at rest; 5-7 minute break; 10 minutes exercise	8 extrinsic asthmatics (adolescents)	Oral-mouthpiece	Rest, then exercise; mean V_e ~ 52 l/min	Post exercise (4-5 minutes)--significant decrease in $V_{max\,50}$ (44%) $V_{max\,75}$ (50%), $FEV_{1.0}$, (23%). Significant increase (67%) in R_t. Shortness of breath (3 subjects), wheezing (5 subjects). Baseline values not restored 20 minutes post exposure. No delayed effects.	Indicates constriction in both large and small airways in asthmatics. Symptoms indicative of clinical significance. Suggests resting exposure (30 minutes) does not result in prolonged (7 minutes) desensitization to subsequent SO_2/exercise exposure.	Koenig et al. (1981)
1.0 ppm SO_2 with and without 1 mg/m^3 NaCl droplet aerosol	30 minutes at rest; 5-7 minute break; 10 minutes exercise	8 atopic adolescents (not extrinsic asthmatics)	Oral-mouthpiece	Rest, then exercise V_e ~ 24-56 l/min[4]	SO_2: Significant decrease in $FEV_{1.0}$ (24%), $V_{max\,50}$ (29%), and $V_{max\,75}$ (34%). Trend toward increased R_t (31%) not significant. Combination: not significantly different from SO_2 alone. No change in FRC.	Indicates constriction in both large and small airways. Comparisons of combination aerosols indicate atopics nearly as sensitive as adolescent asthmatics, both groups substantially more sensitive than normals.	Koenig et al. (1982a)
0.75 ppm	10 minutes plus[3]	23 asthmatics	1)Oral-mouthpiece 2)Chamber	Exercising V_e ~ 40 l/min	Oral: Significant increase in SRaw (mean = 320% over post-exercise control) and symptom scores; significant decreases in FVC, $FEV_{1.0}$, PEFR, Vmax 50, Vmax 25. Chamber: Significant increases in SRaw (mean = 185% over post-exercise control, significantly less than for oral) and symptom scores; significant decreases in same function parameters as in oral, differences between modes not significant. Significant increase in sham SRaw for both modes (52-55% over pre-exercise) No delayed symptoms.	Indicates constriction in large and small airways, greater with oral breathing. Symptoms, changes in small airways not diminished by free breathing. Effects suggestive of clinical and physiological significance. Clean air EIB unusually high. No individual data, although some "high responders" identified.	Linn et al. (1982b)

TABLE 5-4. SELECTED CONTROLLED HUMAN STUDIES OF QUANTITATIVE INTEREST
(Continued)

Concentrations	Duration	Number/ Type Subjects	Exposure Mode	Exercise Status[1]	Observations[2]	Comments	Reference
0.5 ppm	10 minutes	7 asthmatics	Oral-mouthpiece	1)Exercising V_e ~ 35 l/min[5] 2)Resting	Significant increase (mean = 115%) in SRaw (all 7 subjects responded) with exercise. Shortness of breath and wheezing reported in 3 subjects. No change in SRaw after resting exposure.	Indicates constriction in large airways. Symptoms suggestive of clinical significance.	Sheppard et al. (1981a)
0.5 ppm	10 minutes	5 asthmatics	Oral-mouthpiece	Exercising V_e ~ 27 l/min	Increase in SRaw (mean = 40% over post exercise control) in 4 subjects. One subject (with largest increase in SRaw) reported increase in respiratory symptoms(unspecified).	Statistics not given. Indicates constriction in large airways. Symptoms suggestive of clinical significance. Generally consistent with Sheppard et al., 1981 above.	Linn et al. (1982a)
0.5 ppm	60 minutes	24 asthmatics	Chamber (nasal)	Intermittent exercise alternating with rest (10 min.) V_e ~ 27 l/min	No significant changes in SRaw or FVC. No increase in symptoms. No delayed symptoms.	Indicates no effects on large or small airways, symptoms. No detectable health effects. Suggests decreased effects of nasal vs. mouthpiece exposures, somewhat smaller ventilation.	Linn et al. (1982a)
0.5 ppm	5 minutes	6 asthmatics	1)oral-mouthpiece 2)oronasal-facemask 3)nasal-facemask mouth occluded	Exercising V_e ~ 40 l/min	Oral: Significant increase in SRaw (mean = 90%) all subjects responded. Five subjects reported shortness of breath, the sixth reported throat irritation; 3 subjects coughed. No symptoms during sham (humidified air). Oronasal: Significant increase in SRaw (mean ~50%) all subjects responded. Four subjects reported shortness of breath, nose and throat irritation, 2 had no symptoms. Nasal: Significant increase in SRaw (mean ~28%) 5 subjects responded. One subject reported shortness of breath, two reported nose and throat irritation. Oral SRaw significantly greater than nasal. Other differences between exposure routes not statistically significant.	Indicates constriction in large airways is diminished by nasal, oronasal breathing, but under these conditions bronchoconstriction remains. Symptoms suggestive of clinical significance, increase going from nasal to oronasal to oral.	Kirkpatrick et al. (1982)
0.5 ppm	180 minutes	40 normals, 40 mild asthmatics	Oral-chamber with nose clip	Resting	No functional changes in 39 of 40 normals. One "normal" 13 yr. old had decreased MMFR (18%), increased Raw (30%), after exposure. Small decrease (2.7%) in MMFR in asthmatics. Delayed symptoms (3 subjects).	Small changes in MMFR less than diurnal variation, no clinical significance. The "normal" responder may have been an undiagnosed asthmatic. Delayed nocturnal responses not replicated in other studies.	Jaeger et al. (1979)
0.25 ppm	10 minutes	7 asthmatics	Oral-mouthpiece	Exercising V_e ~ 30 l/min[5]	Significant increase in SRaw (mean = 30%); 3 of 7 subjects showed increase. No symptoms.	Small change in large airways; health significance in these subjects unclear.	Sheppard et al. (1981a)
0.25 ppm	60 minutes	24 asthmatics	Chamber	Intermittent exercise alternating with rest (10 minutes) V_e ~ 27 l/min	No significant change in SRaw or FVC. No increase in symptoms during exposure. No delayed symptoms.	Indicates no effects on large or small airways, symptoms. No detectable health effects. Suggests decreased effect of nasal mouthpiece (Sheppard et al., 1981) exposure, somewhat smaller ventilation, high humidity.	Linn et al. (1982a)
0.1 ppm	10 minutes	2 asthmatics selected for sensitivity at 0.25, 0.5 ppm	Oral-mouthpiece	Exercising V_e ~ 35 l/min[5]	Significant, but small (unquantified) increase in SRaw in both subjects. No symptoms.	Small change in large airways; health significance in these subjects unclear.	Sheppard et al. (1981a)

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[1] Exercise expressed in terms of total minute ventilation (V_e). See Table A-1 for example activities, corresponding to these rates. Unless otherwise specified, ventilation rates given represent approximate mean values derived from information presented in the study.

[2] See Appendix C for a brief description of various functional tests listed here. Percentage changes listed here represent changes in group mean over comparable clean air exposure situation.

[3] Exposure continued while pulmonary function tests were administered.

[4] Koenig (1982).

[5] Sheppard (1982).

subjects. The remaining chamber studies of exercising healthy adults indicate that functional changes are not expected in such subjects at SO_2 levels $\leq$ 0.5 ppm (CD, p. 13-49).

b) Asthmatics and Atopics (1 ppm)

Asthmatics and, to a lesser extent, atopic subjects appear significantly more sensitive than normals to SO_2 induced bronchoconstriction. This is illustrated most clearly in the work of Sheppard et al. (1980) for SO_2 alone and Koenig et al. (1982a) for SO_2 and salt aerosol, both of which provide comparative responses of the three groups under comparable exposure conditions.

Five studies in Table 5-4 have examined the effect of SO_2 on asthmatics and atopics. Activity levels include resting to moderate levels of exercise and ventilation rates. All studies used mouthpieces, which tend to result in greater effects than would be expected for normal breathing and otherwise similar exposures. Thus, effects should not be directly extrapolated to ambient settings without accounting for differences in ventilation and oral configuration. The Koenig group used SO_2 and 1 mg/m^3 salt droplet aerosol, which complicated assessment of the role of SO_2. Nevertheless, empirical results and physicochemical considerations suggest the effects of the combination are largely, if not exclusively, due to SO_2 alone. Results in atopics suggest no significant difference between SO_2 alone and the combination aerosol (Koenig et al., 1982a). Moreover, for this NaCl/SO_2 exposure combination, less than 1% of the SO_2 would be expected to dissolve in the droplet (Section IV), severely limiting the potential for increased SO_2 penetration by a "carrier" mechanism. No sulfuric acid formation is likely to have occurred (McJilton et al., 1976).

The five studies of 1 ppm SO_2 (by two separate groups) are qualitatively consistent. Despite the somewhat large inter- and intra-subject variability in functional parameters noted in these asthmatic subjects, it is clear that all studies found statistically and possibly clinically significant changes in respiratory mechanics. As expected, increased ventilation through exercise (or hyperventilation) resulted in marked increases in airway resistance and perceptible breathing difficulties. Under the ventilation rates, humidity and temperatures used in these studies, no evidence existed of exercise induced bronchospasm (EIB) in clean air. The most notable changes were reported by Sheppard et al. (1981a) for asthmatics after 10 minutes of moderate exercise and mouthpiece exposure. Although direct, quantitative comparisons are not possible due to different measurements, the responses in asthmatics observed by Koenig et al. (1982a) appear to be less severe (but still significant), even though higher exercise rates and longer exposure durations were involved. The lower response might be related to differences in subjects, measurement parameters, or the fact that Koenig's subjects were exposed at rest for 30 minutes prior to exercise exposure while Sheppard's subjects received SO_2 and exercise simultaneously. Of note, however, is that Koenig still observed significant functional changes and symptoms after exercise exposure, even after 30 minutes of "conditioning" at this relatively high concentration. Functional parameters had not returned to baseline values even 20 minutes after exercise.

c) Asthmatics (0.75 ppm)

One recent study has examined the response of exercising asthmatics to natural oronasal and mouthpiece exposures (10 minutes) to 0.75 ppm

SO_2 (Linn et al., 1982b). Although exercise levels (V_e ~ 40 l/min) were lower than used in the study of normal subjects by Stacy et al. (1981), functional responses of free breathing asthmatics to 10 minute exposures were about an order of magnitude or more greater. For mouthpiece exposures, functional responses (SR_{aw}, $FEV_{1.0}$, PEFR, V_{max50}, V_{max25}) were consistent with those reported in the 1.0 ppm SO_2 mouthpiece studies of asthmatics discussed above. For unencumbered breathing, specific airway resistance (SR_{aw}) also increased substantially over clean air controls, but the increase was about 55% of that observed for mouthpiece breathing, presumably reflecting a decrease in SO_2 penetration with oronasal breathing. Based on measured ventilation patterns (Table A-1), under the conditions of this study, the oral ventilation rate for oronasal breathing would be about 50-65% of that for mouthpiece breathing. Decrements in other functional parameters (e.g., $FEV_{1.0}$, V_{max50}) were somewhat smaller for unencumbered than for mouthpiece breathing, but the differences were not statistically significant. This study found a substantial increase in SR_{aw} (55%) in clean, humidified air at room temperature. This increase at V_e ~ 40 l/min is not consistent with the much smaller exercise induced bronchoconstriction reported by Kirkpatrick et al. (1982) and Deal et al. (1979).

Coincident with changes in lung function following SO_2 exposure was a marked increse in symptom scores based on 11 symptom types measured. Unlike SR_{aw}, symptom responses were not significantly mitigated by unencumbered breathing relative to mouthpiece breathing. Symptoms or functional measurements were not reported on an individual basis. The authors did observe "excess" responders and noted the removal of one sensitive subject from the group average because his plethysmograph readings went off the scale of the instrument following both mouthpiece and unencumbered exposures to SO_2. Linn et al. (1982b) concluded that "...our results are consistent with the possibility of a 'high-risk' subpopulation of asthmatics in whom upper respiratory defenses are ineffective, suggested by Sheppard et al. Even with effective upper respiratory defenses, many young adult asthmatics clearly can be expected to show clinically and physiologically significant responses to SO_2 at concentrations of 0.75 ppm or less."

d) Asthmatics (0.5 ppm)

Four studies in Table 5-4 examined 7 different exposures to 0.5 ppm SO_2. The Jaeger et al. (1979) work is somewhat unique in the number of subjects, exercise status (all at rest), and duration of exposure. The major finding is a very small, but statistically significant difference in airway constriction in resting asthmatics, breathing orally with nose clips, but no change in normals. The small change is of no known health significance, but much larger functional responses in one, apparently atopic normal adolescent, and delayed symptomatic responses in this subject and two asthmatics were considered by the authors as indicative of possible concern. Although delayed responses are mechanistically plausible if SO_2 sensitizes asthmatics to subsequent bronchoconstrictive challenge (Reichel, 1972), the issue has not been systematically investigated and other studies have not yet confirmed unequivocal delayed responses following SO_2 exposures (Linn et al., 1982a,b; Koenig et al., 1981).

The other studies of 0.5 ppm SO_2 involve averaging times of 5 to 60 minutes, with varying exercise rates and exposure modes. The most pronounced functional and symptomatic responses were observed by

Sheppard et al. (1981a) for moderate exercise (35 l/min) and mouthpiece exposure. The results of the pilot experiment by Linn et al. (1982a) (exposure identical with somewhat lower exercise, $V_e \sim 27$ l/min) and of the oral exposures of Kirkpatrick et al. (1982) (higher exercise, shorter duration) are qualitatively similar to the Sheppard work, but the responses appear somewhat smaller in the more recent studies. Varying exercise regimes, subject sensitivity, and exposure duration appear sufficient to account for the observed differences. These studies indicate that oral (mouthpiece) exposure with light to moderate exercise can result in effects of concern in asthmatics (CD, p. 13-51). They also suggest the possibility of similar responses at exercise levels high enough to result in comparable oral ventilation rates with free breathing. Because use of a mouthpiece decreases oral resistance to breathing, however (CD, p. 11-11; Cole et al., 1982), it has been speculated that mouthpiece exposures tend to overstate SO_2 effects with free breathing, even with comparable oral flow rates (Proctor, 1981).

Two studies (Linn et al., 1982a; Kirkpatrick et al., 1982) used exposure systems that more reliably simulate natural breathing conditions. Linn et al. (1982a) found no response to 0.5 ppm SO_2 in a chamber exposure. At the exercise levels used by Linn et al., 85% of typical populations would be exclusively nasal breathing, but 15% (mouth breathers) would have oral ventilation rates on the order of 15 l/min, or close to the rate that might be observed for resting mouthpiece breathing (Niinimaa et al., 1981). Based on the negative results of Sheppard et al. (1981a) in resting asthmatics, no substantial effects would be expected under the exposure regime used by Linn et al. (1982a). With a higher total ventilation rate (40 l/min), Kirkpatrick found marked responses after 5 minute face mask exposures to 0.5 ppm SO_2. Both studies found evidence of exercise induced bronchoconstriction in clean air (SR_{aw} increase ~ 15%). Given the conditions and exercise levels, EIB of this magnitude or less is consistent with the work of Deal et al. (1979).

Although not precisely duplicating ambient conditions, no evidence suggests that face masks would result in marked increases in penetration of SO_2 over that obtained for natural oronasal breathing. If the asthmatics in the Kirkpatrick study were similar to the "mouth breathing" subjects in the Niinimaa study, the oral component of ventilation (27 l/min) would be virtually identical to that used in the Linn pilot study. Perhaps fortuitously, the increases in airway resistance over clean air/exercise control in these studies are also quantitatively similar (50% versus 40%). In essence, these studies indicate the possibility of significant increases in airway resistance and symptoms in free breathing asthmatics after short (5 to 10 minute) exposures to 0.5 ppm SO_2, but only with moderate or higher exercise levels. The Kirkpatrick study further permits direct comparisons of oral only, oronasal (facemask), and nasal only exposures at similar exercise levels. All three routes result in significant increases in bronchoconstriction suggesting that at high enough ventilation rates, the effective fraction of SO_2 removed by the nose decreases, permitting increased penetration.

e) Asthmatics (< 0.25 ppm)

Two studies in Table 5-4 examined exposure of asthmatics to SO_2 levels of $\leq$ 0.25 ppm. Sheppard et al. (1981a) found evidence of bronchoconstriction in 3 of 7 subjects with exercise and mouthpiece exposures at 0.25 ppm and in the two most sensitive subjects, small (as indicated by graph) changes at 0.1 ppm. The significance of these small changes, unaccompanied by symptoms, is unclear. Linn et al. (1982a) found no response for free breathing asthmatics at 0.25 ppm SO_2.

2. Short-term Exposures

The few controlled human studies that have examined SO_2 exposures over periods of several hours to days are of limited quantitative value due to unrealistic exposure levels and patterns, limited or unreported activity levels, restricted numbers of endpoints measured, and in one case, confounding influence of medication and limited description of procedures and results (Appendix B). Weir and Bromberg (1972) found no evidence of long-term functional changes (tests of large and small airways, gas exchange region) or symptoms in 12 healthy subjects and 7 smokers with early signs of small airway impairment following continuous 5 and 4 day exposures to 0.3 ppm SO_2. Exercise, if any, was not reported. Effects on nasal cross sectional area and mucociliary clearance, suggested by 6-hour exposures to higher levels (1 ppm, Andersen et al., 1974), were not examined. Functional parameters in the smokers were highly variable under sham conditions, limiting evaluation of potential SO_2 responses. The study indicates that exposure to a constant level of SO_2 at 0.3 ppm results in no pulmonary function changes in normal adults or smokers with signs of impaired small airways. Effects of similar exposures to other sensitive groups or effects of more realistic variations about the mean SO_2 levels have not been assessed.

The principal basis for developing quantitative assessments of acute effects of ambient exposures of SO_2 on a daily basis is community epidemiological studies. Such studies can provide strong evidence for the existence of pollution effects resulting from community exposures. The major limitations of epidemiological studies as discussed in Section 14.1.1 of the criteria document include: 1) inadequate and inconsistent measurement of the exposure burden of individuals; 2) variability in the measurement of health endpoints (e.g., lung function, hospital admissions, frequency of symptoms) and in the sensitivity of populations studied; 3) failure to fully control for confounding, or covarying factors, such as cigarette smoking and socioeconomic status; 4) difficulty in distinguishing the effects of SO_2 from particulate matter and other pollutants, and; 5) inability to establish a causal relationship, or negate one, based on statistical associations.

Recognizing these limitations, the following discussion outlines those studies cited by the criteria document as providing the most reliable quantitative information as well as other studies that provide useful information on the relative importance of SO_2 without allowing derivation of specific levels. Epidemiological evidence for quantitative assessment of SO_2 is drawn from the same limited set of British studies previously evaluated in the particulate matter staff paper (EPA, 1982b). These studies are summarized in Table 5-5. The description and evaluation contained in Section V-D of the particulate matter staff paper will not be repeated here. The discussion will focus on the relative importance of SO_2 in producing the observed effects.

The early London mortality studies (Martin and Bradley, 1960; Martin, 1964; Ware et al., 1981) found marked associations among smoke, SO_2, and mortality in the concentration ranges indicated in Table 5-5. The presence of dense fog may have been particularly important in these winters. These studies did not attempt to separate the effects of SO_2

TABLE 5-5. SUMMARY OF EPIDEMIOLOGICAL STUDIES PROVIDING MOST USEFUL CONCENTRATION/RESPONSE INFORMATION FOR SHORT-TERM SO_2 EXPOSURES

Observed Effects	Time	Population	24-Hr Levels Where Effects Are Likely (CD, Table 14-7)		Comments	Study
			BS (as $\mu g/m^3$)*	SO_2 ($\mu g/m^3$)		
Clear increases in daily mortality	1958-60 winters	Metropolitan London	$\geq$ 1000	$\geq$ 1000 (0.38 ppm)	1958-59 winter episodes. Unusually foggy with peak pollution. (Lawther, 1963; Holland et al., 1979).	Martin and Bradley (1960) Martin (1964)
Likely increases in daily mortality	1958-60 winters 1958-72 winters	Metropolitan London	500-1000	500-1000 (0.19-0.38 ppm)	"Greatest certainty" of increases with BS, SO_2 > 750 $\mu g/m^3$, but indications of small increases with BS < 500 $\mu g/m^3$ (CD, Table 14-7). Significant correlation most consistent for smoke.	Martin and Bradley (1960) Martin (1964) Ware et al. (1981) Mazumdar et al. (1981)
Daily worsening of health status in bronchitics	1954-68 winters	180, and later ≈ 1000 chronic bronchitic patients, London	250-500	500-600 (0.19-0.23 ppm)	Well designed. Peak values above daily average may have been important. Minimum levels for any "significant" response were 250 $\mu g/m^3$ BS, 500 $\mu g/m^3$ SO_2; significant associations among sensitive subgroup at lower levels (Lawther et al., 1970).	Lawther et al. (1970) Lawther (1958)

*British Smoke - A pseudo-mass indicator related to small particle ($\leq$ 4.5 μm) darkness (i.e., carbon content). Mass relationships approximate.

from particulate matter. In their analysis of 14 London winters, Mazumdar et al. (1981) attempted to partition the effects of the two pollutants using two approaches: 1) categorizing mortality by quartiles of pollutant levels (e.g., 4 ranges of smoke levels within each of 4 ranges of SO_2); and 2) regression in models that considered smoke and SO_2, their squares and their interactions separately and jointly.

Examination of the quartile analyses shows that for the limited number of comparisons where concentration of one pollutant is held relatively constant while the other varies, there is a clear tendency for mortality to rise with increasing smoke, but no consistent rise in mortality with increasing SO_2 levels. In the regression analysis, when pollutants were considered separately, both SO_2 and smoke were significantly associated with mortality. When the pollutants were considered together, only smoke is consistently positively and significantly associated with mortality. The coefficient for SO_2 is positive (nonsignificant) for the episodic (> 500 $\mu g/m^3$ smoke and SO_2) period.

On the basis of their analysis, the authors conclude that smoke (particles), but not SO_2, is influential in causing mortality and that no evidence of synergism was found. They further developed dose-response models for smoke, but not SO_2, which extended to smoke levels below 500 $\mu g/m^3$. The criteria document cautions that "serious questions can be raised regarding specific details concerning the quartile analysis used and the validity of reported conclusions regarding the separation of BS from SO_2 effects" (CD, p. 14-21). It seems reasonable to conclude, however, that while the 14-winter analyses suggests the possibility of small increases in the risk of mortality at smoke levels less than the "likely effects level" (500 μg/m^3), the published analyses provide no such suggestion for SO_2 exposures below the likely effects levels listed in the criteria document. Further examination of the London data set and available analyses appear warranted before more definitive conclusions can be reached.

Other time-series analyses of daily variation in mortality and pollution in New York City between 1963 and 1972 indicate weak but positive associations between non-episodic mortality and daily levels of particles, but not SO_2 (Schimmel and Murawski, 1976; Schimmel, 1978). The criteria document states that these latter analyses "create serious doubt regarding reported associations between mortality and non-episodic SO_2 levels present in New York City during the 1963 to 1972 period" (CD, p. 14-26). Unfortunately, reliance on a single, central Manhattan monitoring station as an estimate of pollutant exposures for the entire New York City area "precludes clear quantitative statements regarding possible effect or no-effect levels based on these results" (CD, p. 14-26).

The work of Lawther et al. (1970) on bronchitics is widely regarded as being among the most reliable investigations of the effects of particles and SO_2 on morbidity. The levels indicated in Table 5-5 are, in the authors' judgment, the lowest leading to any significant response. They suggested that the reported aggravations in health may have reflected the effects of brief exposures to the maximum concentration occurring during the day. These peaks were several times the 24-hour averages, but, because of the wide dispersion of subjects and the variation in the magnitude and timing of such peaks across the study areas, the impact of peak values could not be examined directly.

Moreover, it is possible that repeated variations in exposures during the day may have lead to effects not accounted for by single daily peak exposures.

Of some interest in this regard is the study by the same group (Lawther et al., 1973, 1974a,b,c) of acute decrements in ventilatory function in four healthy adults and two bronchitics. Responses were associated with variations in pollutant levels measured at their place of work or treatment (St. Bartholemew's Hospital). After multiple regression to remove time trend effects, SO_2 concentrations explained the largest proportion of residual variance in peak flow rates, with clearest association shown after walking exercise in heavy pollution. Quantitative conclusions from this study are not possible.

Two additional morbidity studies involved hospital and emergency room visits in London (Martin, 1964) and Steubenville, Ohio (Samet et al., 1981). Although both suggest associations between admissions and exposures to particles and SO_2, neither used as sensitive a health index for quantitative purposes as did Lawther's group.

In summary, the more quantitative epidemiological studies suggest that effects may occur at SO_2 levels at or above 0.19 ppm (500 $\mu g/m^3$), 24-hour average, in combination with elevated particle levels. The strongest evidence relates to effects on bronchitics. Whether the effects are due (in part) to SO_2 alone, heterogeneous formation of sulfuric acid or other irritant aerosol, particles alone, peak values, or repeated variations around the daily mean cannot be unequivocally determined.

3. Chronic Exposures

The relationship between long-term exposure to air pollution and health has been extensively studied, but few of the studies provide sound data or consistent findings sufficient to make quantitative conclusions, especially regarding SO_2. Geographic comparisons of morbidity (Appendix B.5, EPA, 1982b) and mortality rates among populations suffer from many limitations (CD, Section 14.1.1.1 and p. 14-35). There are no studies that are useful in delineating quantitative relationships between chronic exposures to sulfur oxides and mortality, while only one quantitative study of chronic morbidity effects possibly involving SO_2 has been identified in the criteria document. The results of this study are outlined below.

Lunn et al. (1967, 1970) studied respiratory disease and lung function of school children in four areas of differing pollution levels in Sheffield, England. At age 5, both chronic upper respiratory infections and lower respiratory tract illnesses were associated with residence in more polluted areas. The criteria document notes that the effects were likely with annual SO_2 levels of 181-275 $\mu g/m^3$ (0.07-0.1 ppm) SO_2 in combination with 230-301 $\mu g/m^3$ smoke (CD, Table 14-8). The criteria document concludes that "no-effect" annual levels of SO_2 or smoke cannot be determined from a follow-up study conducted by the same investigators (Lunn et al., 1970; CD, p. 14-49).

VI. FACTORS TO BE CONSIDERED IN SELECTING PRIMARY STANDARDS FOR SULFUR OXIDES

This section, drawing upon the previous evaluation of scientific information, outlines the key factors that should be considered by the Administrator in deciding what pollutant indicator to use for sulfur oxides, establishing the level of primary standards, and designating appropriate averaging times and frequency criteria. Preliminary staff recommendations on the most appropriate policy options in each of these interrelated areas are presented.

A. Pollutant Indicator, Averaging Times, and Form of the Standards

1. Pollutant Indicator

Elevated levels of SO_2 associated with health effects in historical episodes were always accompanied by high levels of particles. As discussed in previous sections, it has been difficult to separate the effects of SO_2 and particles in these cases, and either or both pollutants might have been surrogates for some hitherto unidentified "active agent." Based on laboratory studies, particles may increase respiratory tract penetration of absorbed SO_2 or otherwise enhance toxicity by chemical or physical transformations. Combined SO_2/particulate matter indicators have been suggested to account for these potential interactions.

In its previous assessment (EPA, 1982b), the staff with CASAC concurrence, recommended a separate standard for particles but left open the possibility of linking SO_2 standards to particle levels. In evaluating this possibility, the following factors should be considered:

1) Recent evidence from controlled human studies shows that SO_2 acting alone can, at realistic peak concentrations, produce substantial

decrements in pulmonary function and increase respiratory symptoms in exercising asthmatics (Section V-B).

2) In contemporary U.S. atmospheres, TSP, PM_{10}*, and fine particle readings all may be poor indicators of those aerosols most likely to interact with SO_2. The acidity of sulfuric acid and other ambient sulfates, major components of fine particle mass, precludes substantial additional adsorption of SO_2. The presence of fog, low temperature, and high humidity, which are not necessarily associated with high particle mass, are more likely to lead to interactions (Section IV).

3) The particulate matter standard should ensure that particle levels are lower than those likely to be associated with health effects, alone or in the presence of SO_2. The principal transformation products of SO_2/particle interactions (i.e., sulfates) form a major component of PM_{10} and, as such, are included in the recommended particle standards (EPA, 1982b).

4) Although the issue is unresolved, SO_2 may interact in an additive or synergistic manner with other criteria pollutants, notably ozone.

5) Sources of high SO_2 levels often are well controlled with respect to primary particulate matter, and many sources of particles emit no SO_2.

Given the health effects data, it appears that a separate SO_2 standard is appropriate, whether or not a combination standard is also adopted. In view of the above considerations, it is not clear that a combination standard would result in any improvement in health protection over separate standards for SO_2 and particles, each chosen with due consideration of the potential for interactive effects. Unless health related advantages can be identified, the additional complexities involved in specifying and implementing combination SO_2/particle standards do not appear warranted.

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*Particles less than a nominal 10 μm, termed "Thoracic Particles" in the particulate matter staff paper (EPA, 1982). PM_{10} is the indicator recommended by the staff and by CASAC for use in revised standards for particulate matter.

2. Averaging Time(s)

The current averaging times for the sulfur oxides primary NAAQS are annual and 24-hour; they were based on available epidemiological studies. The studies outlined in Section V still provide qualitative and quantitative support for short-term standards, but do not provide clear quantitative support for the current annual standard. Although some studies suggest the possibility of effects associated with long-term exposures to community air pollution containing SO_2 and particles, data on respiratory tract deposition (Appendix A), long-term animal, and community studies (Appendix B) indicate that any such effects are more likely to be the result of exposures to repeated short-term peaks than of continuous lower level exposures. The possibility of effects from such lower level exposures cannot, however, be ruled out. In the absence of more quantitative data, it appears appropriate to base the decision on whether to retain an annual average SO_2 standard on the long-term air quality that is anticipated as a result of the implementation of short-term standards. Under the current standards, maintenance of the 24-hour standard results in attainment of the annual standard in the vast majority of sites. Nevertheless, air quality analyses indicate that the exceptions where the annual standard is "controlling" include heavily populated urban areas such as New York City, Chicago, and Philadelphia (Frank and Thrall, 1982). Thus, although the health data are limited, the potential for increased exposure in populated areas suggests that it is appropriate to consider retaining an annual average standard.

Qualitative and quantitative (Table 5-5) studies support a 24-hour averaging time. Some epidemiological investigators (Lawther et al., 1970) have speculated that the observed health effects might be largely due to short-term peaks on the order of an hour. While controlled human exposures to peak levels clearly indicate functional and symptomatic responses, these studies cannot capture the full range of exposures, potential effects, and sensitive groups examined in the acute epidemiological studies. Therefore, retention of a 24-hour averaging time is appropriate.

Both animal and controlled human studies (Table 5-1) have reported respiratory responses to peak SO_2 exposures lasting minutes to hours. The more quantitative controlled human studies (Table 5-4) provide evidence sufficient to warrant consideration of an additional shorter averaging time for SO_2 standards. Most of the studies indicating effects of concern involve averaging times of 1-hour or less. Based on practical considerations related to monitoring, modeling, data manipulation and storage, and implementation, the staff recommends consideration of a 1-hour averaging time in addition to the 24-hour period. In considering the level of a 1-hour standard, the range of shorter-term (5-10 minute) peak levels associated with 1-hour averages should be recognized, because effects have been observed following controlled exposures as brief as 5 to 10 minutes.

3. Form of the Standard

The staff recommends that the 24-hour and possible 1-hour and annual standards be stated in a statistical form rather than a deterministic form (the current 24-hour standard is not to be exceeded more than once per year). For the short-term standards this could be accomplished by either: 1) setting a standard where an allowable number of exceedances of the standard level would be expressed as an average or expected number per year, or, 2) setting a standard where a given percent of the daily maximum hourly values would be expected to be less than or equal to the standard level. The emissions reductions to be achieved in the required control program would be based on a statistical analysis of the monitoring or modeling data over a multi-year period (e.g., the preceding 3-year period). In the case of the possible annual standard, this would be accomplished by determining an expected value based on multi-year monitoring data.

The statistical form can offer a more stable target for control programs and, with reasonably complete data, is less sensitive to truly unusual meteorological conditions than the deterministic form. The general limitations of the deterministic form are discussed more fully elsewhere (Biller and Feagans, 1981). Recognition of these limitations has led EPA to promulgate or propose statistical forms for the ozone and carbon monoxide standards.

For the purposes of this paper, ranges for standards presented later will assume a statistical form. Alternative numbers of exceedances may be desirable and should be considered. Multiple exceedances are helpful in that they permit more stable portions of the air quality distribution to be used as implementation targets. In so doing, the interaction between multiple exceedance alternatives and the level of the standards can be specified (Frank and Thrall, 1982).

Two general approaches to establishing multiple exceedance standards include:

1) Establish a standard level and permit more exceedances of that level. With this approach, increasing the number of exceedances increases the risk associated with just attaining the standard.
2) Allow more exceedances, but adjust the level of the standard downward so as to provide health protection roughly equivalent to that associated with a single exceedance.

Figure 6-1 illustrates the relationship between standard level and exceedances for 24-hour SO_2 values based on the empirical data, and several assumed log normal distributions (Frank and Thrall, 1982). For example, the figure shows that a standard with five allowable exceedances has an average ratio of 0.67. This means that on the average, the level of a 24-hour standard with five allowable exceedances should be 67 percent of the level associated with a standard with one allowable exceedance in order to provide the same degree of protection. If this average adjustment factor of 0.67 were employed, however, approximately half of the locations that would just meet this standard would exceed the level associated with the standard with one allowable exceedance. If protection equal to or greater than that associated with a single exceedance standard was desired at 90% of the sites, the figure indicates that the appropriate ratio would be 0.44, resulting in a lower standard level. In this case about 90% of the sites might be controlling to a greater extent than might be required under a single exceedance standard. Trade-offs among risks, degree of over-control, and the robustness of air quality targets should be considered when deciding upon the number of exceedances. Comparable analyses have also been prepared for alternative 1-hour standards (Frank and Thrall, 1982).

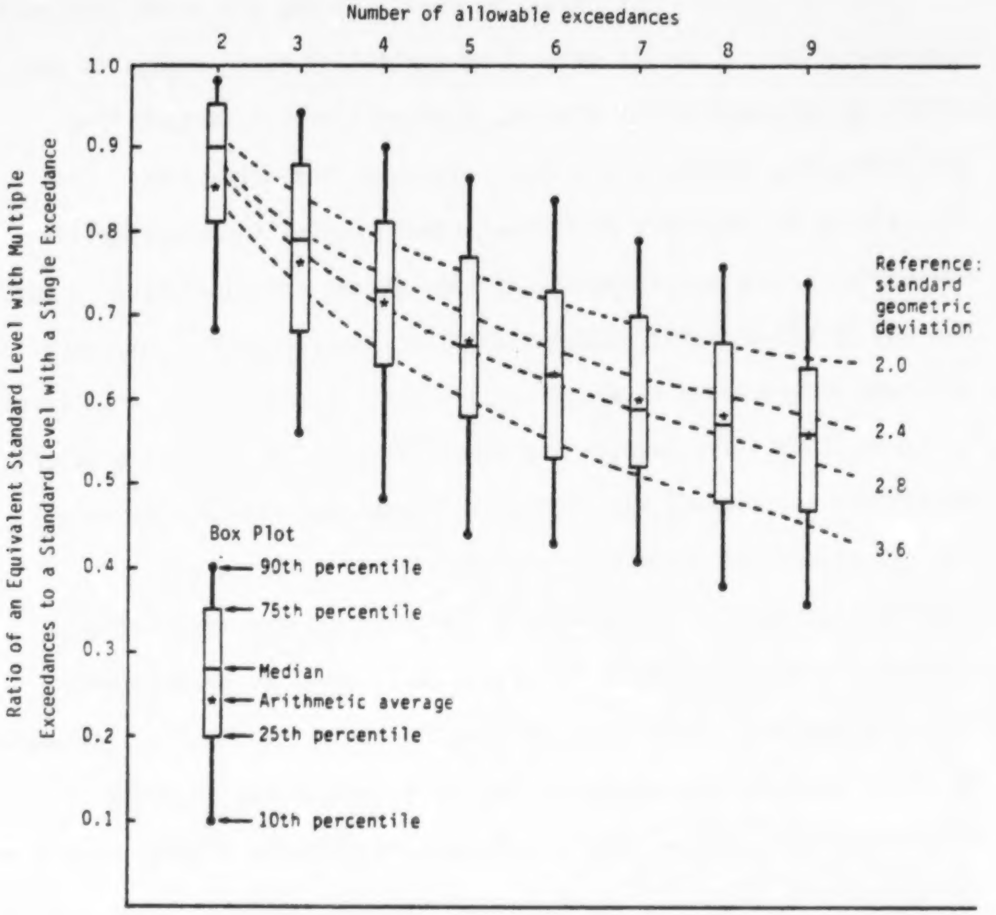

Figure 6-1. Factors needed to render a Multiple-Exceedance Standard Equivalent to a Single Exceedance Standard (Frank and Thrall, 1982). The box plots are based on 130 site-years with maximum 24-hour value > 0.12 ppm; the dotted lines are derived from lognormal distributions and are presented for comparative purposes.

B. Level of the Standard

1. General Considerations

The major scientific basis for selecting SO_2 standards that have an adequate margin of safety comes from controlled human exposures and community epidemiological studies, with mechanistic support from toxicological, deposition, and air chemistry investigations. The limitations of available controlled human studies for quantitative evaluation of ambient exposures of populations are summarized in Section V-D and in the criteria document (Section 13.1). Such studies provide accurate measurements of specific pollutant exposures, but are limited in exposure regimes, numbers and sensitivity of subjects, and severity of effects tested, and may involve artifacts not representative of ambient exposures. Community epidemiological studies, while representing real world conditions, can only provide associations between a complex pollutant mix and a particular set of observable health endpoints. It follows that, although the scientific literature provides substantial information on the potential health risks associated with various levels and exposure patterns of SO_2, selection of appropriate levels, frequency criteria, and averaging times remains largely a public health policy judgment.

The following sections present a brief staff assessment of the concentration/response relationships suggested by the most significant controlled human studies and epidemiological studies in the criteria document and indicate how these studies may be applied in developing ranges for decision-making on standards for SO_2. The presentation also outlines a qualitative assessment of the key factors, based on contemporary U.S. exposures, that affect the margin of safety associated with the ranges of standards derived from these studies. This includes identification of those important aspects of the qualitative human and animal studies as summarized in Section V that should be incorporated into margin of safety considerations. Peak (< 1-hour), short-term ($\leq$ 24-hour), and long-term (annual), exposures are discussed separately.

2. Peak (< 1-hour) Exposures

a) Derivation of Ranges of Interest from Controlled Human Exposure Studies

Controlled human studies providing useful quantitative information on peak SO_2 exposures are summarized in Section V-D and Table 5-4. Although all of these studies provide important information, many involved use of a mouthpiece or nose clip. As the criteria document points out with regard to quantitative results in these studies, "caution should be employed in regard to any attempted extrapolation of these observed quantitative exposure-effect relationships to what might be expected under ambient conditions" (CD, p. 13-50). With due regard to this guidance, Table 6-1 presents a preliminary staff assessment of the controlled human studies most useful in developing a range of interest for selecting a 1-hour SO_2 standard. The table focuses on those studies involving free breathing (chamber or facemask) exposures and resting oral exposures. The former studies provide the closest approximation of free breathing; the latter involve low (~ 10 l/min) oral ventilation rates which would be exceeded in "mouth" breathers by oronasal breathing with even light to moderate exercise (Table A-1). Although the oral component of breathing may be different for oronasal and mouthpiece breathing at comparable flow rates (Cole et al., 1982), it is both prudent and consistent with the available SO_2 studies to assume that no substantial differences exist in SO_2 induced responses

TABLE 6-1. STAFF ASSESSMENT OF KEY CONTROLLED HUMAN EXPOSURE STUDIES

SO_2 Concentration (5-60 minutes)	Observed Effects	Implications
1 ppm	Functional changes, possible symptoms in resting asthmatics, oral (facemask or mouthpiece) exposure.[1]	Strong suggestion that at this level even light exercise for "mouth" breathing asthmatics would result in comparable or more marked changes.[3]
0.75 ppm	Functional changes in free breathing normal healthy subjects, moderate to heavy exercise. No health effects.[2]	Comparable oronasal exposures in asthmatics, or atopics could result in effects of significance.[3]
	Functional changes, symptoms in free breathing (chamber) asthmatics, moderate exercise.[4]	Significant effects in mild asthmatics with moderate exercise.
0.5 ppm	Functional changes, symptoms in oronasal (facemask) breathing, asthmatics with moderate exercise but not in asthmatics (chamber) with light exercise.[5]	Lowest level of significant response for free breathing.
0.25 ppm	No observed effect in free breathing subjects.[3]	Significant effects unlikely.

[1] Sheppard et al. (1980), Koenig et al. (1980). The second study used SO_2 in combination with saline aerosol.

[2] Stacy et al. (1981); Bates and Hazucha (1973).

[3] Sheppard et al. (1981a); Linn et al. (1982a); Koenig et al. (1982a).

[4] Linn et al. (1982b).

[5] Kirkpatrick et al. (1982); Linn et al. (1982a).

for these breathing modes. Inferences made in the "implications" column are supported by those mouthpiece studies that demonstrate the high sensitivity of asthmatics and atopics to SO_2 and the substantial enhancement of response in these subjects with increased ventilation.

The table indicates that functional changes and symptoms are likely in "mouth" breathing asthmatics exposed to short-term peaks of 1 ppm SO_2 while involved in everyday activities such as walking outdoors. The finding of functional changes in free breathing normals with moderate to heavy exercise ($V_e \sim 60$ l/min) at 0.75 ppm SO_2 suggests that asthmatics and atopics, who are substantially more sensitive than normals (Table 5-3; CD, p. 13-50), would experience significant responses if engaged in exercise producing similar ventilation rates (e.g., moderate jogging). Indeed, even with a lower exercise rate ($V_e \sim 40$ l/min), Linn et al. (1982b) found "clinically and physiologically significant" responses in free breathing young adult asthmatics at 0.75 ppm SO_2. Results at 0.5 ppm SO_2 are mixed, but do suggest effects in asthmatics with moderate exercise ($V_e \sim 42$ l/min), such as light jogging. This is the lowest level of response for free breathing reported in the published literature as of this writing. Studies of oronasal breathing (Appendix A) suggest that with higher exercise (50-60 l/min), oral ventilation rates (35 l/min) would be equivalent to those in the mouthpiece exposures of 0.25 ppm SO_2 which produced small increases in airway resistance in some asthmatics; no perceptible symptoms would be expected (Sheppard et al., 1981a).

In evaluating these results in the context of decision-making on possible standards, the following considerations are important:

1) The Significance of the Observed or Anticipated Effects to Health.

Little controversy exists that a full asthma attack represents an adverse health effect. In the extreme case, status asthmaticus, which occurs in as many as 10% of adults hospitalized for asthma (Senior and Lefrak, 1980), the situation can be life threatening. In less extreme cases, day to day activities must be terminated until medication that relieves the symptoms and eases breathing can be administered. Even though relief is usually rapid following medication, an insult that requires the use of medication to permit routine functioning might well be considered an adverse health effect.

The controlled human exposure studies of SO_2 discussed above were designed to avoid precipitating serious asthma attacks or irreversible effects in exposed subjects. The question arises, then, as to whether the observed responses themselves represent adverse effects or serve as indicators of potentially more serious consequences for larger populations exposed in ambient settings.

The criteria document concludes that temporary small changes in pulmonary function observed in normal adults are of less concern than functional changes and symptoms observed in asthmatics. The document summarizes the issue as follows (CD, p. 13-51):

> Probably of most concern are marked increases (> 10 percent) in airway resistance and symptomatic effects (wheezing, dyspnea) observed by Sheppard et al. (1981a) in a group of mild asthmatics with oral exposure via mouthpiece to 0.5 ppm (1.3 mg/m^3) sulfur dioxide during exercise. A recent article (Fischl et al., 1981) and accompanying editorial (Franklin, 1981) in the medical literature discuss the inclusion of indices of airway obstruction and presenting symptoms such as wheezing and dyspnea among factors to be considered in attempting to predict the need for hospitalization of asthma patients following initial emergency room treatment (e.g., bronchodilator therapy, etc.) for asthmatic attacks.

Based on this criteria document discussion, it appears that the results of studies listed in Table 6-1 begin to be of some concern to health when bronchoconstriction is accompanied by noticable symptoms. This occurs for exercising asthmatics exposed to SO_2 levels at or above 0.5 ppm. The scientific literature does not, however, provide sufficient information to specify a concentration at which effects of concern should be considered adverse. In making such a judgment, the Administrator should consider the discussion above and the following additional factors:

a) In all cases, the bronchoconstriction and symptoms were transient and reversible. The data do not provide direct evidence of long-term consequences from repeated peak exposures, but the possibility of such effects cannot be ruled out.

b) Particularly at lower concentrations with free breathing functional changes were moderate to small (Δ SR_{aw} ~ 0 to 50%) and within the range of variability observed for day to day changes in many asthmatics. At 0.75 ppm, effects were more substantial (Δ SR_{aw} ~ 180%) (Table 5-4).

c) Most studies utilized mild, young-adult or adolescent asthmatics. Even with the limited number of subjects studied to date, some individuals appear particularly sensitive, exhibiting functional changes and symptoms markedly greater than average. Even more sensitive individuals may exist in the population of "mild" asthmatics; those with more severe asthma may also be more sensitive to SO_2 induced bronchoconstriction.

d) Although the reported responses cannot be interpreted as overt asthma attacks, the combination of bronchospasm and symptoms might be perceived by some subjects as a "mild" attack; this could well result in curtailment of desired physical activities.

e) It is unclear whether psychological factors can induce asthma attacks (NIAID, 1979). If they can, however, perception of symptoms and bronchospasm induced by SO_2 could trigger more serious consequences in suggestible subjects.

f) Given the limited combination of concentrations, subjects, activity levels, and other environmental conditions studied to date, firm conclusions about situations in which SO_2 would likely induce asthma attacks are not possible. Even if it is judged that the functional and symptomatic effects seen in available studies are not themselves adverse, they could be considered as possible indicators of more serious attacks that are clearly adverse.

2) Relative Effect of SO_2 Exposure Compared to Exercise, Other Stimuli.

One of the tests used in characterizing asthmatics is evidence of exercise induced bronchospasm (EIB). The phenomenon has been extensively investigated (e.g., Deal et al., 1979) and appears to be related to temperature and relative humidity of inspired air. Under the exercise and other test conditions (~ 20°C, 70-95% RH) of most SO_2 studies, EIB is usually small (increase in $SR_{aw} \leq 15\%$) (Linn et al., 1982a; Sheppard et al., 1981a; Deal et al., 1979); Linn et al. (1982b) observed a somewhat larger group mean EIB

(SR_{aw} ~ 55%). At low temperatures and humidities (-12°C, 0% RH) more substantial increases in airway resistance can occur (Deal et al., 1979). Under these environmental conditions, the EIB found by Deal et al. (1979) (Δ SR_{aw} ~ 40%) with clean air mouthpiece breathing is smaller than the increase in airway resistance (50% over exercise control) seen by Kirkpatrick with facemask exposure to 0.5 ppm SO_2 at the same exercise rate. Thus, although EIB alone may limit the maximal exercise rate of asthmatics, SO_2 enhances the effect, further limiting activity or increasing the risk of a more serious response. The combination of SO_2, exercise, and cold dry air has not yet been tested.

A number of other stimuli may induce bronchoconstriction in asthmatics (Table 6-2). This does not diminish the importance of responses potentially induced by peak SO_2 levels.

TABLE 6-2. TRIGGERS OF ASTHMATIC ATTACKS (NIAID, 1979)

I. Known
  A) Allergen
  B) Drugs
    1) Allergy
    2) Aspirin intolerance
    3) Pharmacologic effects
  C) Exercise
  D) Industrial (avocational and occupational exposure)
  E) Infections
  F) Reflexes

II. Probable
  A) Air pollutants
  B) Chemical irritants
  C) Sinusitis
  D) Vasculitis (periarteritis)

III. Possible
  A) Emotions
  B) Endocrinologic imbalance
  C) Weather

3) Probability of Most Sensitive Exposures

Peak 1-hour SO_2 levels in excess of 0.5 ppm are rare with current U.S. air quality, and almost always occur only in the vicinity of major point sources (Tables 4-1, 4-2; Appendix D). Shorter term (5 to 10 minute) peaks at these levels may be somewhat more common, but no systematic data exist. Moreover, indoor SO_2 levels are almost always substantially lower than outdoor levels (CD, p. 5-117). Thus, effects appear likely only for situations involving asthmatics undergoing light to moderate exercise outdoors relatively near (< 10 km) major point sources in conditions resulting in peak (> 0.5 ppm, 5 to 10 minutes) SO_2 levels. Preliminary analyses (Appendix D) suggest that several hundred thousand asthmatics and atopics may live in the vicinity of such sources, but because the frequency and extent of levels in excess of 0.5 ppm is low, the probability that an exercising asthmatic will be located in the same time and area with such peaks appears small. Quantitative analyses of the frequency of occurrence of such exposures are not yet available. Although under current air quality conditions, such situations must be infrequent, they present the possibility of significant health effects.

Some data suggest that rapid rises in SO_2 levels, such as those involved in many of the controlled studies, are more likely to produce effects than are more gradual rises. As discussed in Section V-B, however, the rapid rise might result from a) movement from indoors to outdoors, b) onset of exercise resulting in a rapid rise in SO_2 at sensitive respiratory tract receptors, c) movement into an area of peak levels (by vehicle or otherwise), as well as, d) an actual rapid increase in ambient levels at a point.

4) Variance about the 1-hour average.

The controlled studies in Table 5-4 indicate that effects occur within 5-10 minutes but do not necessarily worsen with continued exposure over the course of an hour. Five and ten minute averages will vary about the 1-hour mean. Thus, for an area just attaining a 1-hour standard of 0.5 ppm, 5 or 10 minute peaks will be higher. Based on typical distributions, the peak is likely to be within a factor of 1.4 to 2.4, or less than 1.2 ppm (Larsen, 1968; Burton and Thrall, 1982). As the ratio of 5-minute to 1-hour concentrations increases, the geographical extent of the peak tends to decrease.

Based on the above evaluation of the studies and related factors, the staff believes that an appropriate range of interest for a possible 1-hour SO_2 standard is 0.25 to 0.75 ppm. The lower bound of 0.25 ppm represents a 1-hour level for which maximum 5 to 10 minute peak exposures are not likely to exceed 0.5 ppm, the lowest level where potentially significant responses in asthmatics have been observed with free breathing, but with a facemask. Although mouthpiece experiments suggest the possibility of modest functional changes produced by 10 minute exposures to 0.25 ppm SO_2, with moderate exercise, the effects themselves are not clearly of health significance. Furthermore, heavy exercise rates are required to produce comparable or greater oral ventilation for free breathing, reducing the probability of exposure to this condition. The upper bound of the range (0.75 ppm) represents a level at which (based on the results in free breathing asthmatics and normals, the increased sensitivity of asthmatics and atopics in mouthpiece experiments, and the results of oronasal exposures at 0.5 ppm), the risk of effects appears high. Based on normal air quality variations a 1-hour standard of 0.75 ppm would permit 5-10 minute peaks in excess of 1 to 2 ppm during the peak hours, and would permit multiple hours in which the 5-10 minute peak would exceed 0.5 to 0.75 ppm, even when the 1-hour average is within this range.

Independent of frequency of exposure considerations, 1-hour concentrations at the high end of the above range would provide little margin of safety for exercising asthmatics. The low frequency with which such peak values would occur in the presence of active sensitive subjects tends to enhance the margin of safety.

b) Additional factors to be considered in evaluating margin of safety and risks - peak exposures

Additional factors that should be considered in evaluating a margin of safety for a 1-hour standard include:

i) Interaction with Other Pollutants

The studies in Table 6-1 were done with SO_2 alone. As discussed in Section V, additive or greater than additive responses might occur where peak SO_2 levels occur in combination with O_3 or particles. The available data do not provide clear evidence for synergism in either case, but controlled exposures have not examined such combinations in sensitive asthmatics. Because peak SO_2 exposures occur during morning to early afternoon hours (Figure 4-1), combinations with O_3 at or near the standard level (0.12 ppm) are possible. Because peak SO_2 levels near combustion sources will be accompanied by high NO_x levels, simultaneous peaks of SO_2 and O_3 near these sources are not likely. Significant health related interactions between SO_2 and NO_2 have not been demonstrated.

ii) Risks for Other Sensitive Groups, Effects Not Evaluated

Based on the available data, asthmatics and atopics appear to be the most sensitive segments of the population with respect to peak SO_2 induced functional changes. To the extent the suggested range is protective of these groups, the risk of functional effects in other groups appears small. The other major effects of concern (changes in clearance, aggravation of bronchitis, genetic toxicity, and mortality) have not been evaluated adequately in controlled human studies, but may result from repeated peak exposures over longer time periods. These are addressed in the following sections.

3. Short-term (24-hour) Exposures

a) Derivation of Ranges of Interest from Epidemiological Studies

Although a number of epidemiological investigations provide qualitative evidence for the effects of short-term exposure to SO_2 in combination with particles, the criteria document indicates that those most useful for developing quantitative conclusions include a series of studies and reanalyses of daily mortality in London (Martin and Bradley, 1960; Martin, 1964; Ware et al., 1981; Mazumdar et al., 1981; CD, p. 14-16 to 14-24) and studies of bronchitis patients in London (Lawther et al., 1970). These studies are briefly evaluated in Section V-D (Table 5-5). The staff assessment of these studies for deriving ranges of interest for 24-hour SO_2 standards is summarized in Table 6-3 and discussed below.

The London mortality studies have been characterized by the criteria document as suggesting that notable increases in excess mortality ocurred in the range of 500-1000 $\mu g/m^3$ British Smoke (BS) and SO_2 (0.19-0.38 ppm) and are most likely when both pollutants exceeded

TABLE 6-3. STAFF ASSESSMENT OF SHORT-TERM EPIDEMIOLOGICAL STUDIES

Effects/ Study	Measured Sulfur Dioxide - $\mu g/m^3$(ppm) - 24 hour mean		
	Daily Mortality in London[1]	Aggravation of Bronchitis[2]	Combined Effects Levels
Effects Likely[3]	500-1000(0.19-0.38)	500-600(0.19-0.23)	500(0.19)
Effects Possible	-	< 500(0.19)	< 500(0.19)

[1] Deviations in daily mortality from mean levels examined in 3 studies encompassing individual London winters of 1958-59 and 14 aggregate winters from 1958-72. Early winters were dominated by high smoke and SO_2, principally from coal combustion emissions, and with frequent fogs (Martin and Bradley, 1960; Ware et al., 1981; Mazundar et al., 1981).

[2] Examination of symptoms reported by bronchitics in London. Studies conducted from the mid-1950's to the early 1970's (Lawther et al., 1970).

[3] CD, Table 14-8.

about 750 $\mu g/m^3$ (0.29 ppm SO_2). As indicated in Table 6-3, these estimates represent judgments of the most scientifically reliable "effects likely levels" for daily SO_2 (and BS) and mortality, at least in the context of historical London pollution exposures. Because of the severity of the health endpoint and the need to provide an adequate margin of safety in standard setting, it is important to determine whether the data support the possibility of health risks below these "effects likely levels." As discussed in the criteria document (CD, Section 14.3.1.2) and the particulate matter staff paper (EPA, 1982b), the London mortality studies and reanalyses do support the possibility of a monotonic dose-response for particles, with no obvious "threshold" at 500 $\mu g/m^3$.

The situation with respect to SO_2, however, is much less clear. When SO_2 alone is compared with daily mortality deviations, an apparent association persists at levels below 500 $\mu g/m^3$ or 0.19 ppm (Ware et al., 1981; Mazumdar et al., 1981). However, if attempts are made to account for particles and weather variables, the association between mortality and pollution on non-episodic days (BS, $SO_2 < 500\ \mu g/m^3$) persists for smoke but not for SO_2 (Mazumdar et al., 1981). This analysis also questions the role of higher SO_2 levels (> 500 $\mu g/m^3$ or 0.19 ppm) with respect to mortality effects. The criteria document concludes, however, that the effects of SO_2 and BS at these higher concentrations cannot clearly be separated (CD, p. 14-24). Table 6-3 reflects the staff conclusion of Section V-D, namely that the published evidence does not suggest a significant risk of increased mortality for exposures to SO_2 alone at concentrations below the likely effects levels listed in the criteria document.

Lawther's studies of bronchitic patients began during periods of high pollution (1954) and continued through the time when levels were considerably lower (e.g., 1967-68; mean winter SO_2, 204 $\mu g/m^3$, 0.08 ppm; BS, 68 $\mu g/m^3$). Lawther et al. (1970) found an association between peak pollution and health status of bronchitics and that responses declined as controls reduced pollutant levels. Because of the nature of the study, effects were related to peak daily concentrations, but the authors felt the effects were more likely the result of brief exposures to short-term peaks "several-times the 24-hour average." While this suggestion is plausible, the available data do not permit any quantitative evaluation. The mechanisms of aggravation of bronchitis might involve responses (e.g., slowed clearance) other than the functional changes observed in asthmatics. Thus, 1-hour standards based on protecting asthmatics might not be adequate for bronchitics. Therefore, 24-hour, or to a lesser extent, longer-term pollutant averages, should be used to indicate the possibility of repeated short-term levels of concern. Lawther's suggestion that 24-hour averages of 250 μg/m^3 smoke and 500 μg/m^3 (0.19 ppm) SO_2 represent "the minimum pollution leading to any significant reponse" appears reasonable, although the possibility that short-term peaks of concern may occur at lower 24-hour levels cannot be discounted. The criteria document notes that a summary of results for selected patients for the winter 1967-68 (Table III, Lawther et al., 1970) suggests a statistically significant correlation between SO_2 (as well as smoke, sulfuric acid, and temperature) and symptom scores for a winter with only one day of SO_2 > 500 μg/m^3 (0.19 ppm) and BS $\geq$ 250 μg/m^3. While such simple correlations do not demonstrate effects at lower levels, they do suggest that 500 μg/m^3 (0.19 ppm) SO_2 (and 250 μg/m^3 BS) may not be absolute thresholds for the most sensitive bronchitis patients (CD, p. 14-53).

Both the mortality and bronchitic studies represent population groups among the most sensitive to pollutant effects. Taken together, as in Table 6-3, the studies indicate that effects are likely with SO_2 levels at or above 500 μg/m^3 (0.19 ppm) in the presence of smoke levels of 250 μg/m^3 to 500 μg/m^3. Thus, 500 μg/m^3 (0.19 ppm) represents an upper bound for the range of interest for 24-hour SO_2 standards. Although the data suggest that effects may be possible at lower levels and, therefore, a need to include an adequate margin of safety below the more certain effects levels, the studies provide no scientific basis for establishing a lower bound for a range of interest for 24-hour SO_2 standards. In the absence of such data, it seems reasonable to recommend the level of the current standard (365 $\mu g/m^3$ or 0.14 ppm) as a lower bound. This level was previously judged to provide an adequate margin of safety from the effects under consideration here. Although the effects of SO_2 cannot be unequivocally separated from particles, for reasons specified in Section VI-A, a separate SO_2 standard is desirable. For days in which particulate matter approaches the high end of the recommended range (350 $\mu g/m^3$ as PM_{10}; EPA, 1982b), simultaneous SO_2 levels at the high end of the above range (0.19 ppm) would provide no clear margin of safety. With lower particle levels, the margin of safety increases.

b) Additional Factors to be Considered in Evaluating Margin of Safety -- Short-term Exposures

The range of interest was derived from British data representing two effects categories and London pollution from 1958 to 1972. In considering standards within this range the following additional factors should be considered:

i) Interactions with Other Pollutants or Conditions

As noted above, interactions with expected maximum particle concentrations have been taken into account to establish the range of interest. Interactions of SO_2 with ozone and other photochemical oxidants have not been evaluated on a daily basis. The results of short-term (2-hour) studies at high SO_2 and O_3 levels do not permit clear conclusions (Appendix B).

Based on the experiences in London and other areas and solubility considerations, conditions involving low temperature, high humidity fogs with substantial ammonia, with or without high primary particles, might exacerbate the effects of SO_2.

ii) Relative Exposure

Based on measurement of indoor exposures and ventilation reported by Lawther et al. (1970), indoor pollutant exposures in British residences more closely tracked outdoor levels than is the case in more tightly sealed U.S. residences. Thus, for comparable outdoor concentrations, the overall exposure to maximum 24-hour outdoor pollution was likely to have been greater in urban areas of Great Britain than in contemporary U.S. exposure situations. Since many of the more sensitive individuals may be confined indoors, the extent of increased mortality or symptoms would tend to be lower in the U.S. than observed at comparable levels in British studies.

iii) Risks for Other Sensitive Groups, Effects not Evaluated

Based on the evaluation of toxicological, controlled human, and qualitative epidemiological data, Section V-B and Table 5-2 identify a number of effects that would be observed or anticipated to occur in sensitive groups as a result of such exposures. The studies used to derive the range addressed: 1) premature mortality in very sensitive individuals with chronic respiratory and cardiovascular diseases, individuals with influenza, and the elderly; and 2) morbidity (aggravation of disease) in bronchitic patients. Because it is reasonable to expect morbidity at or below levels at which mortality occurs in these sensitive groups, the London mortality studies, which involved a large population, also may be considered as a relatively sensitive indicator of morbidity risks. Thus, to the extent that the London data suggest a risk of small increases in mortality at levels as low as 0.19 ppm, some risk of morbidity is possible at or somewhat below this level. This risk should be considered in evaluating potential standards.

Other groups not expressly addressed by the short-term British studies are children and asthmatics. Daily exposures to particles and SO_2 appear to be associated with increased symptoms of respiratory disease, particularly in sensitive children (Lebowitz et al., 1972). Repeated peak SO_2 exposures might reduce resistance to infection by slowing nasal or other mucociliary clearance rates (Section V-B). Other qualitative studies suggest possible small effects of repeated peak or 24-hour exposures to SO_2 on lung function in children in contemporary North American cities (Becklake et al., 1978; Dockery et al., 1981). The significance of these preliminary findings is unclear at this time, and no reason exists to suggest important effects below the range of interest. Potential effects on sensitive asthmatics are most likely related to peak exposures and are addressed by the recommendations with regard to a 1-hour standard.

The above discussion addresses, in part, several of the major effects categories of expected effects of SO_2 outlined in Section V-B. With respect to those not addressed: 1) Qualitative evidence summarized in that section suggests that repeated acute exposures to high levels of SO_2 and community air pollution may affect clearance and other host-defense mechanisms, possibly resulting in increased infections and disease. 2) The question of potential mutagenesis/carcinogenesis of SO_2 alone or in combination with carcinogens (BaP) is unresolved. The available toxicological data mostly involve extended repeated exposures to very high exposures, but do not permit quantitative evaluation. Epidemiological studies indicate that cigarette smoking is the major determiniant of lung cancer, but do not rule out the possibility of a small effect of high historical levels of air pollution. Both peak (1-hour) and short-term (24-hour) ranges would maintain these as well as annual SO_2 concentrations in U.S. cities to levels well below these historical values, but would not prevent long-term air quality in some heavily populated areas from deteriorating to levels above those allowed under current standards (Frank and Thrall, 1982).

Studies of hospital admissions or emergency room visits, although a crude indicator of morbidity, sometimes can provide some suggestion of the effects of pollution on several of the above categories. The results of Samet et al. (1981), although essentially negative, provide a suggestion of a very small, but statistically significant, association between emergency room visits for respiratory diseases and SO_2 levels between 2 to 369 $\mu g/m^3$ (0.001-0.14 ppm) and TSP levels in the range of 14 to 700 $\mu g/m^3$.

4. Long-Term (Annual) Exposures

As discussed in Section V, despite a number of studies of long-term community exposures of SO_2 in combination with particles and other pollutants, the criteria document concludes that there is little quantitative data useful in developing long-term concentration response relationships for SO_2. Based on the work of Lunn et al. (1967, 1970) long-term SO_2 levels should be maintained below 0.07 ppm (180 $\mu g/m^3$), a level not approached in contemporary U.S. atmospheres. The health basis for limiting annual SO_2 levels beyond those permitted by shorter-term standards is suggested by the more qualitative evidence summarized in Section V-B and also outlined in the previous section. These potential effects of interest for which quantitative data are not available include effects on clearance and other host defense systems, and, to a lesser extent, potential mutagenicity or co-carcinogenicity of SO_2. The major concern is whether repeated SO_2 peaks permitted by 24-hour or 1-hour ranges in area-source dominated populations centers might, after some long time period, result in increased risk of such effects. While the available data do not provide strong evidence for substantial risks on an individual basis, the analysis of Frank and Thrall (1982) suggests that elimination or substantial relaxation of the current annual standard could result in increased exposures to large numbers of people in several heavily populated urban centers. The potentially large increase in exposed individuals and the qualitative evidence for effects should be considered in deciding whether to maintain an annual standard at or above the current level of 0.03 ppm (80 $\mu g/m^3$).

5. Relationships Among Averaging Times

An important consideration in evaluating potential standards are the interrelationships among 1-hour, 24-hour, and annual averaging times. Although several recent analyses are available (Frank and Thrall, 1982; Burton et al., 1982; MES, 1982) information in this area remains incomplete. Data from the approximately 900 sites used in Tables 4-1 and 4-2 show that attainment of the current annual standard (0.03 ppm SO_2) would not prevent multiple exceedances of the lower bound of the recommended ranges for both 1-hour and 24-hour standards (Figure 6-2). This figure indicates that a national annual standard would probably not be a useful surrogate for shorter term standards without being unnecessarily restrictive in some areas. Conversely, as noted above and in Appendix D, current and alternative shorter term standards (24-hour, 3-hour, 1-hour) would not prevent long-term levels from exceeding the current annual standard in some population-oriented sites

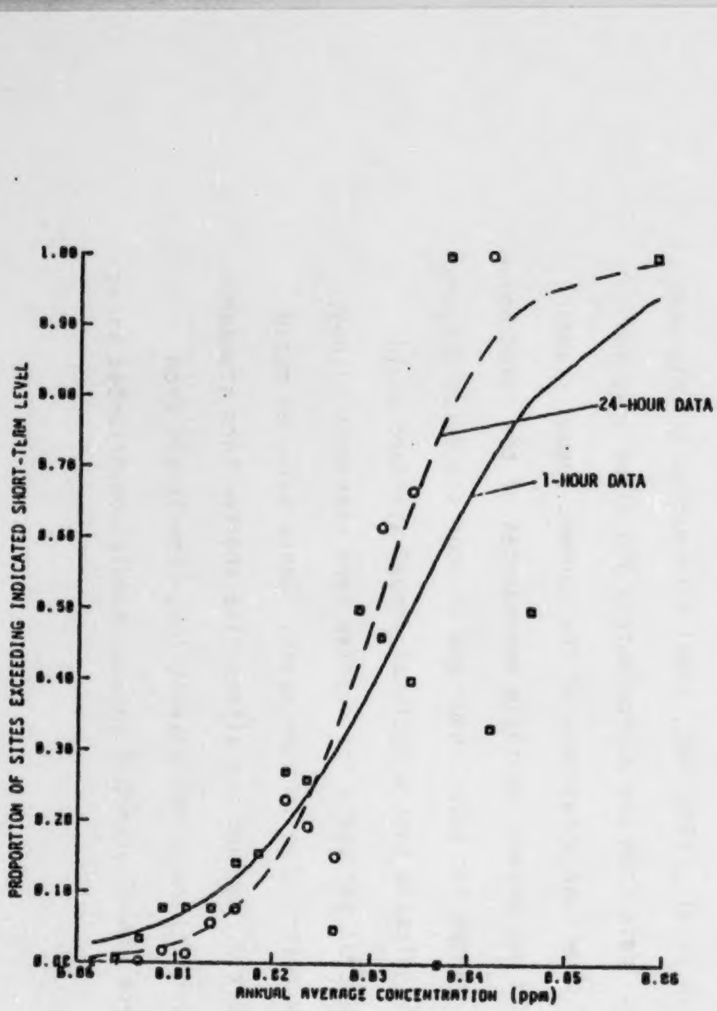

Figure 6-2. Proportion of sites recording a given annual average SO_2 concentration, with 2 or more short-term SO_2 concentrations exceeding 0.5 ppm for 1 hour (□) or 0.14 ppm for 24 hours (○)(Thrall, 1982).

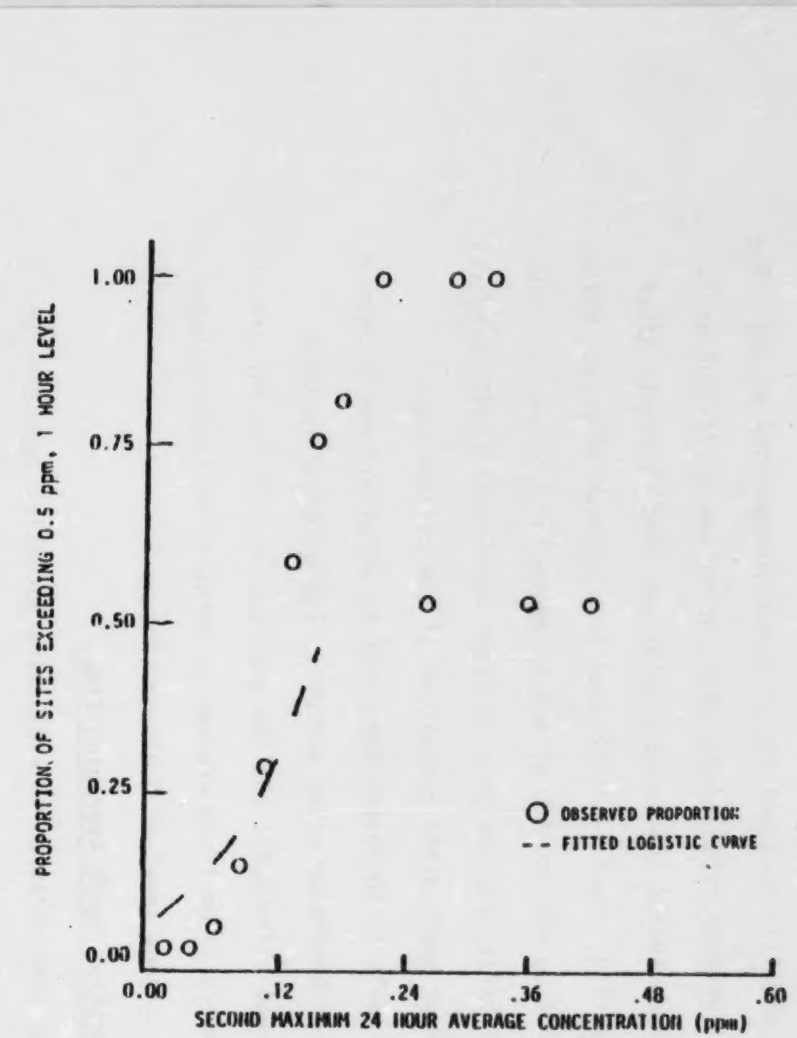

Figure 6-3. Proportion of sites recording a given second maximum 24 hour average concentration, with 2 or more 1 hour SO_2 concentrations exceeding 0.5 ppm (Thrall, 1982).

which are few in number, but represent substantial numbers of people potentially exposed (Frank and Thrall, 1982).

It is also apparent that a 1-hour standard would not guarantee attainment of the 24-hour standard at all site types. For example, analysis of continuous SO_2 data at population oriented sites in 4 major urban areas suggests that attainment of a 0.5 ppm 1-hour maximum standard in these areas would result in a 24-hour maximum of 0.21 ppm (550 $\mu g/m^3$) (Johnson, 1982a). The situation is reversed at many sites dominated by large point sources (Frank and Thrall, 1982).

The question of whether a 24-hour standard is a useful surrogate for 1-hour effects has been examined by air quality and modeling analyses (Appendix D). The adequacy of a 24-hour surrogate depends on site type, level and number of exceedances considered adequate for protecting health, and the degree of over-control required vs a 1-hour standard. Figure 6-3 shows the proportion of sites with second 1-hour maxima in excess of 0.5 ppm as a function of second 24-hour maxima for the 900 sites noted above. These data indicate that with attainment of the current 24-hour standard, over 40% of the sites would have second hourly maxima in excess of 0.5 ppm. An even higher proportion of sites can be expected to have second hourly maxima in excess of 0.25 ppm. The air quality and modeling analyses summarized in Appendix D suggest that the current 24-hour standard effectively limits 1-hour maxima at population-oriented sites. At many sites dominated by strong point sources, however, the current 24-hour standard would be a useful surrogate for a 1-hour standard only if multiple (2 to over 20/yr) exceedances of SO_2 levels in the range of 0.5 to 0.75 ppm were considered acceptable. Even a more stringent 24-hour standard of 0.12 ppm would not substantially improve

1-hour air quality at many sites with high 1-hour values. Still tighter 24-hour surrogates would be overly stringent at sites with currently acceptable air quality. Relaxing the 24-hour standard to a level in the upper portion of the range of interest (0.16 to 0.19 ppm) could permit a substantially larger number of sites with second maximum hourly values in excess of 0.75 ppm.

The simulation modeling of large point sources of SO_2 (1000 megawatt power plant) suggests that the current secondary 3-hour standard provides substantially better protection against 1-hour peaks than does the 24-hour standard, and might itself be a useful surrogate. In this simulation, the worst site is predicted to experience 3 to 4 expected exceedances/year of 0.5 ppm and only 1 expected exceedance per year of 0.75 ppm. The air quality analysis of Frank and Thrall (1982) does not suggest substantially improved protection with the 3-hour standard, but because it is based on only 1 or 2 monitors per source, the air quality analysis is less reliable on this point.

The analysis of air quality relationships suggests that no single averaging time will provide the same degree of protection and control afforded by the other averaging times in all situations. The current 24-hour standard would prevent 1-hour peaks in the range of interest from occurring in most population oriented sites, but would allow multiple exceedances of these values in many source oriented sites. Similarly, the 24-hour standard limits high annual values in most, but not all sites of interest. The current 3-hour secondary standard limits 1-hour peaks even more than the 24-hour standard, but does not materially affect long-term urban values. In essence, while additional analyses of alternative averaging times are needed, the work to date suggests that implementation of the current suite of SO_2 standards (annual, 24-hour, 3-hour) provides substantial protection against the direct effects of SO_2 identified in the scientific literature. This permits consideration of reaffirming the existing SO_2 standards as a reasonable policy option following the current criteria and standards review.

C. Summary of Staff Conclusions and Recommendations

The major staff conclusions and recommendations made in Section VI, A-B are briefly summarized below:

1) Laboratory studies show that peak ambient levels of SO_2, acting alone, can cause health effects in humans. Consequently, a separate SO_2 standard is still appropriate. The additional complexities involved in specifying combination SO_2/particle standards do not appear warranted in terms of public health protection.

2) Support for an annual standard at or near current levels is largely qualitative. Nevertheless, because short-term standards alone would not prevent increases in annual mean concentrations in some heavily populated urban areas, consideration should be given to retention of a primary annual standard for SO_2. Based on a series of recent controlled human studies, consideration of a new peak (1-hour) SO_2 standard is also recommended. The 24-hour and potential annual and 1-hour standards should all be expressed in statistical form; the decision on the allowable number of exceedances for the 24-hour and potential 1-hour standard should be made in conjunction with establishing a level for the standards.

3) Based on a staff assessment of controlled human exposures to peak (minutes to hours) SO_2 concentrations, the range of 1-hour SO_2 levels of interest is 0.25 to 0.75 ppm (650 to 2000 $\mu g/m^3$). The lower bound represents a 1-hour level for which the maximum 5 to 10 minute peak exposures do not exceed 0.5 ppm, which is the lowest level where potentially significant responses in free (oronasal) breathing asthmatics have been reported in the published literature as of this writing. The upper bound of the range represents concentrations at which the risk of significant functional and symptomatic responses in exposed sensitive asthmatics and atopics appears high. In evaluating these laboratory data in the context of decision making on possible 1-hour standards, the following considerations are important: (a) the significance of the observed or anticipated responses to health, (b) the relative effect of SO_2 compared to normal day to day variations in asthmatics from exercise and other stimuli, (c) the low probability of exposures of exercising asthmatics to peak levels, and (d) five to ten minute peak exposures may be a factor of two to three greater than hourly averages.

Independent of frequency of exposure consideration, the upper bound of the range contains little or no margin of safety for exposed sensitive individuals. The limited geographical areas likely to be affected and low frequency of peak exposure to active asthmatics if the standard is met add to the margin of safety. The data do not suggest other groups that are more sensitive than asthmatics to single peak exposures, but qualitative data suggest repeated peaks might produce effects of concern in other sensitive individuals. Potential interactions of SO_2 and O_3 have not been investigated in asthmatics. The qualitative data, potential pollution interactions, and other considerations listed above should be considered in determining the need for and evaluating the margin of safety provided by alternative 1-hour standards.

4) Based on a staff assessment of the short-term epidemiological data, the range of 24-hour SO_2 levels of interest are 0.14 to 0.19 ppm (365 to 500 $\mu g/m^3$). Under the conditions prevailing during the London studies (high particles, frequent fogs, winter), the upper end of the range represents levels at which effects may be likely according to the criteria document. The risk of health effects should be lower when translating these results to U.S. settings with particle levels at or below the ambient standards.

The uncertainties with respect to interactive effects with particles or other pollutants and the nature of effects are important margin of safety considerations. In the absence of quantitative scientific evidence for a level where effects are unlikely, the level of the current standard is recommended as a lower bound. This level was previously judged to provide an adequate margin of safety from the same effects under consideration here. Qualitative data from animal toxicology, controlled human studies and community epidemiology suggest risks of potential effects (e.g., slowed clearance) as well as the existence of sensitive groups (e.g., children) not evaluated in the more quantitative studies. These factors as well as potential pollutant interactions, exposure characteristics and whether the 24-hour standard is intended to act as a surrogate for a 1-hour standard, should also be considered in evaluating the margin of safety associated with alternative standards in the range of 0.14 to 0.19 ppm.

5) Although the data are inconclusive and uncertain, the possibility of effects from continuous lower level exposures to SO_2 cannot be ruled out. Given the lack of epidemiological data suggesting long-term effects of SO_2 at or near the levels of the current annual standard, however, no quantitative rationale can be offered to support a specific range of interest for an annual standard. Nevertheless, air quality analyses summarized in Appendix D suggest that short-term standards in the ranges recommended in this paper would not prevent annual levels in excess of the current standard in a limited number of heavily populated urban areas. Because of the possibility of effects from a large increase in population exposure, consideration should be given to maintaining a primary annual standard at or above the level of the current standard.

6) Analyses of alternative averaging times to date suggest that while any single standard might not be a suitable surrogate for other averaging times, implementation of the current suite of primary and secondary SO_2 standards (annual, 24-hour, 3-hour) provides substantial protection against the direct health and welfare (see Section VII) effects identified in the scientific literature as being associated with ground level SO_2 air quality. This permits the consideration of reaffirming the existing SO_2 standards as a reasonable policy option, following the current criteria and standards review. Factors favoring such an option include the substantial improvements likely in information on 1-hour effects over the next few years, the uncertainties in

long-term effects data, the possibility of substantial changes in SO_2 control strategies prompted by regional effects, and the practical advantages of not requiring premature formulation and implementation of a new SO_2 regulatory program associated with revising standards at this time.

VII. CRITICAL ELEMENTS IN THE REVIEW OF THE SECONDARY STANDARD

This section discusses information drawn from the criteria document that appears most relevant in the review and possible revision of secondary standards for sulfur oxides. Three major categories of welfare effects are examined. Within each category, the paper presents 1) a brief summary of relevant scientific information, 2) an evaluation of potential quantitative relationships between SO_2 and effects, and 3) a staff assessment of whether the available information suggests consideration of secondary standards that differ from the recommended primary standards. Preliminary staff recommendations on policy options for secondary standards are also presented.

A. Vegetation Damage

1. Nature of Effects and Factors Affecting Plant Sensitivity

Plant responses to SO_2 exposure may result in physiological and biochemical effects, foliar injury, and reductions in growth and yield. The specific response varies with the pollutant concentration, duration of exposure, and is enhanced or mitigated by certain biological and environmental factors.

Information on the mechanisms of toxicity of SO_2 suggests that plant responses are strongly linked to the penetration of SO_2 and accumulation of sulfite and bisulfite within plant cells. Since sulfate is considered to be much less toxic than sulfite and bisulfite, toxic effects are believed to occur when the rate of accumulation exceeds the rate of conversion of bisulfite and sulfite to sulfate (Thomas, 1951).

In general, there is a progression of effects that can be expected following either short-term or long-term (repeated peak or continuous) exposure. At the lowest reported response levels, short-term exposures tend to be associated with potentially reversible physiological effects (e.g., gas exchange rates, enzyme activities). As exposure levels increase, foliar injury and reductions in growth and yield may result. However, reductions in growth and yield are not always accompanied by foliar injury, and conversely, foliar injury is not always a reliable indicator of growth and yield (CD, p. 8-11).

More specifically, the types of effects can be summarized as follows:

a) Physiological and Biochemical Effects

Physiological and biochemical changes may be expected to precede the development of foliar injury and changes in growth and yield. Although foliar injury is the most obvious effect of SO_2 on plants, it is only the end result of a series of events that have occurred at the sub-cellular level of biological organization. Initial changes in photosynthetic and transpiration rates and biochemical status (e.g., enzyme activities, metabolite concentrations) are subtle responses that may be followed by more severe measures of plant injury (CD, p. 8-5).

b) Foliar Injury

Foliar injury appears to be associated with the penetration of SO_2 to substomatal cavities where damage to mesophyll cells may lead to collapse of tissues and changes in leaf color (NAS, 1978; McLaughlin et al., 1979; Evans and Miller, 1975). Short-term exposure to SO_2 produces foliar injury, which varies in appearance from ivory to white in most broadleaf plants to darker colors (e.g., brown, red) in other plants such as conifers (CD, p. 8-10). Long-term exposure to SO_2 is characterized by chlorotic spots or mottling. Leaves are most sensitive to SO_2 exposure just after growth to full development (NAS, 1978, p. 105).

c) Growth and Yield

Effects of SO_2 exposure on growth and yield have been examined, to some extent, in both short-term and long-term exposure studies. Although increases in foliar injury and decreases in growth and yield tend to occur simultaneously when SO_2 exposures are sufficiently high, foliar injury is an imprecise measure of the effect of SO_2 on growth and yield parameters. For example, studies using soybeans report that growth and yield reductions occur with minimal or no accompanying foliar injury (Reinert and Weber, 1980) and it is possible to have foliar injury with no apparent effect on crop yield (Heagle et al., 1974).

Although plant damage may follow long-term exposures, enhanced growth has also been reported when soil sulfur is not sufficient to meet plant needs and atmospheric SO_2 levels are low (CD, pp. 8-7 to 8-10). Noggle and Jones (1979) conclude that low to moderate levels of atmospheric SO_2 can be beneficial for agricultural crops in areas with sulfur deficient soils. In natural ecosystems, however, SO_2 induced increases (or decreases) in plant growth can affect species richness and diversity and might reduce the stability and productivity of such ecosystems (CD, pp. 7-9 to 7-13). Thus, increased yield in natural ecosystems is not always beneficial (CD, pp. 8-9 to 8-10).

The extent, severity, and type of plant response to SO_2 exposure varies with plant genetics, the condition of the plant itself, and environmental conditions. The inherent susceptibility of plants to SO_2 varies greatly among plant species and even among cultivars, varieties, or clones of the same species (CD, pp. 8-12 to 8-14). In general, the influence of genetics on plant susceptibility is stable and does not change unless selection, mutation, or hybridization occurs (NAS, 1978, pp. 101-103; Wilson and Bossert, 1971). Other important factors affecting the severity of damage which should be considered include:

1) The stage of growth at the time of plant exposure (NAS, 1978, pp. 104-105);
2) The plant's nutrient and water status; the later is particularly important because plants are less physiologically active and more resistant to gas exchanges (including pollutant gases) when stressed for water; and
3) Environmental conditions such as the presence or absence of other pollutants, soil moisture (Hill et al., 1974; Zimmerman and Crocker, 1934), wind speed (Ashenden and Mansfield, 1977), temperature (Heck and Dunning, 1978), light (Thomas and Hendricks, 1956) and relative humidity (McLaughlin and Taylor, 1981).

2. Quantitative Relationships

The following general criteria were used to select those studies most relevant to evaluating quantitative relationships:

1) Exposure regimes should be at or near realistic levels anticipated in the ambient environment. The following levels were used as a guide: short-term exposures (minutes to hours) < 1 ppm (2600 $\mu g/m^3$); and, long-term exposures (weeks to years) < 0.1 ppm (260 $\mu g/m^3$).
2) Exposure and growth conditions must be adequately defined.
3) Plant response should be expressed so that effects on exposed plants can be compared to control plants.

Finally, exposure studies not meeting the above criteria may be included if discussion of their validity and significance is an important part of assessing evidence.

Quantitative information on plant response to SO_2 exposure is drawn from controlled and ambient exposure studies. The strengths and weaknesses of both are outlined below.

a) Controlled Exposure Studies

Controlled exposure studies are comprised of greenhouse, environmental chamber, and field chamber studies. Although a common characteristic of these studies is to control plant exposure to pollutants, controlled exposure studies also allow for the control of other environmental variables. Since field chambers allow plants to be grown and exposed under conditions that approximate actual field conditions, experiments employing field chambers are generally considered to reasonably simulate plant growth in the field. Controlled exposure systems have some inherent problems that complicate extrapolation of experimental results to actual field conditions. For example, most of these studies have exposed plants at wind speeds that are lower than those experienced under field conditions. This is expected to reduce pollutant uptake and plant sensitivity (Ashenden and Mansfield, 1977; Nobel, 1974). On the other hand, investigators typically attempt to optimize growth conditions (e.g., soil fertilization, moisture), which should generally increase plant sensitivity to pollution.

i) SO_2 Alone

The most relevant short-term and long-term exposure studies of the effects of SO_2 alone are listed in Table 7-1. The short-term studies suggest that plants are affected by SO_2 exposures of 1.5 to 4 hours duration. Although some early studies reported foliar injury in agronomic crops following single 1-hour exposures to less than 1 ppm (NAS, 1978; Zimmerman and Crocker, 1934), more recent studies have not evaluated the effect of single hour exposures on other biological

TABLE 7-1. CONTROLLED SO_2 EXPOSURE STUDIES

Concentration ppm ($\mu g/m^3$)	Exposure Duration/ Growth Conditions*	Results	References
Short-term			
0.25 (660)	2 Hours	Foliar injury in 7 pine species.	Berry (1971, 1974)
0.50 (1300)	1.5 Hours	No significant change in fresh shoot weight or increase in foliar injury (soybean).	Heagle and Johnson (1979)
0.50 (1300)	2 Hours	No effects in 3 begonia cultivars; 2 snapdragon cultivars. Reductions in shoot weight in 1 of 3 petunia cultivars; 1 of 2 coleus cultivars. Reduction in flower number in 1 of 3 petunia cultivars.	Adedipe et al. (1972)
0.54 (1915)	4 Hours	Foliar injury in 50% of the leaves exposed in Red Kidney Beans. Concentrations as low as 0.4 ppm produced 4% foliar injury and 100% foliar injury was observed at 1.6 ppm sulfur dioxide.	Jacobson and Colavito (1976)
0.75 (1965)	1.5 Hours 2 Exposures Environmental Chamber	Slight but not statistically significant reduction in dry root weight of oats. Authors suggest "threshold."	Heck and Dunning (1978)
0.79 (2070)	4 Hours	Foliar injury in 50% of the leaves exposed in tempo beans. The lowest concentration producing foliar injury was 0.6 ppm. At 1.6 ppm where 82% of the leaf surface area was injured.	Jacobson and Colavito (1976)
1.0 (2600)	2 Hours	Reductions in shoot weight in 1 of 3 petunia cultivars; 2 of 2 coleus cultivars; 1 of 2 snapdragon cultivars. Reductions in flower number in 2 of 3 petunia cultivars; 1 of 2 coleus cultivars. No effect in 3 begonia cultivars.	Adedipe et al. (1972)
1.0 (2620)	1.5 Hours 2 Exposures Environmental Chamber	19% reduction in top dry weight for oat plants harvested at 28 days.	Heck and Dunning (1978)
Long-term			
0.05 (130)	8 Hours/day 5 Days/week 5 weeks	Reductions in root fresh and dry weights of radish plants (Cherry Belle--a sensitive cultivar).	Tingey et al. (1973b)
0.06 (160) (see text)	68 days continuously Plants were grown in closed top field chambers and potted in an artificial soil mixture.	50% reduction in foliar weight of alfalfa. Other measures of plant growth were also depressed.	Neely et al. (1977)
0.067 (190)	26 weeks continuous closed outdoor chambers winter growth open sided greenhouse	Decreases in the dry weight of living leaves (50%), dry weight of stubble (55%) and other growth indices in S23 ryegrass. No effect in wild clones.	Bell and Clough (1973)
0.068 (190)	Exposures of 0.11 (290 $\mu g/m^3$) for 4 to 20 weeks from 9:30 a.m. Monday through 5:00 p.m. Friday	Reductions in dry weight of green leaves of 2 grasses ranging from about 25 to 40% at 20 weeks and other reductions in growth were also observed between 4 and 20 weeks.	Ashenden (1979)
0.05 (131) to 0.2 (524)	10 weeks continuously Closed top field chambers	Potted grafts of old spruce showed a reduction in CO_2 uptake which was well correlated with decreases in both annual growth ring width and wood density. Beech seedlings exposed during winter to SO_2 displayed progressive decreases in terminal bud viability the following spring that were attributed to SO_2 exposure.	Keller (1978, 1980)

*Plants were grown under greenhouse conditions unless otherwise indicated.

endpoints. Studies in Table 7-1 indicate that conifer seedlings are particularly sensitive to SO_2 exposure--a factor which may affect seedling survival. In addition to those studies reporting foliar injury, Adedipe et al. (1972) found that reductions in flower growth and development may also occur at relatively low exposure regimes (e.g., 0.5 ppm for 2 hours).

The long-term exposure studies in Table 7-1 do not necessarily utilize realistic fluctuations in concentration during long-term exposures. The studies on tree species (Keller, 1978, 1980), ryegrass (Bell and Clough, 1973), and radish (Tingey et al., 1971b) were designed to maintain continuous uniform exposure to SO_2. The studies by Keller (1978, 1980) are regarded as careful work demonstrating how extended exposure to SO_2, in sufficient amounts to depress photosynthesis, can reduce plant growth. The study by Tingey and coworkers (1971b) reporting reductions in radish harvest parameters is of particular interest because it found that plants may be affected at relatively low exposure levels. The median concentration (0.06 ppm) in the study by Neely and coworkers (1977) apparently included repeated peak exposures. In this study, the highest single hour daylight concentration during the growing season reached 0.60 ppm SO_2 and the second and third highest peak 1-hour daylight concentrations were 0.42 and 0.40 ppm SO_2, respectively (Neely, 1982). Consequently, in this study, it is not possible to determine the relative importance of repeated peak versus long-term low-level exposure.

ii) Pollutant Mixtures

Studies of the effects of pollutant mixtures show that plants may exhibit different types of responses which are influenced by several variables and are difficult to predict. Three general kinds of responses may follow plant exposure to mixtures of SO_2 and one or more other pollutants.

1) Additive responses. An additive response is a response that would be predicted from the effects of individual pollutants alone. For example, if a 2-hour exposure to either of two pollutants each at 0.10 ppm caused 10 percent foliar injury, 20 percent foliar injury would be expected following simultaneous exposure to both pollutants.
2) Greater than additive or "synergistic" responses. One example of a "synergistic response" is one in which there is no foliar injury from exposure to either pollutant alone and foliar injury is observed following simultaneous exposure to both pollutants. Within the context of plant responses to pollutant exposure a "synergistic" response refers only to the degree of response and does not imply anything about potential mechanism(s) of injury.
3) Less than additive or "antagonistic" responses. Antagonistic responses are expected when exposures are high and effects are relatively pronounced.

Two of these three kinds of responses are found to some degree in the experimental results using various combinations of SO_2 and O_3 or NO_2 shown in Table 7-2. At lower concentrations (e.g., 0.10 ppm NO_2 and 0.05 ppm SO_2), little if any increase in foliar injury is observed. As concentrations are raised (e.g., 0.10 ppm NO_2 and 0.10 ppm SO_2), the increase in foliar injury is greater than additive. At higher concentrations, foliar injury increases for the SO_2 and O_3 but not for the SO_2 and NO_2 exposure mixtures. The variability of response at

TABLE 7-2. EFFECTS OF SINGLE 4-HOUR SO_2 EXPOSURE MIXTURES ON FOLIAR INJURY

a) Percent Leaf Injury[1,4]

Species[2]	Ozone/Sulfur Dioxide Concentration (ppm/ppm) 0/0.10	0.10/0.10	0.10/0.25	0.10/0.50	0/0.50
Alfalfa[6]	2	24	21	60	19
Broccoli	1	34	11	19	0
Cabbage	0	22	14	54	0
Radish	0	50	22	46	1
Tomato	0	50	10	13	0
Tobacco[6] (Bell W_3)	0	95	88	96	0

b) Percent Foliar Injury[3,5]

Species[2]	Nitrogen Dioxide/Sulfur Dioxide (ppm/ppm) 0.10/0.05	0.10/0.10	0.15/0.10	0.20/0.20	0.15/0.20
Pinto Beans	0	11	24	16	4
Oats	0	27	12	10	0
Radish	1	27	24	6	4
Soybean	1	35	20	9	1
Tobacco[6] (Bell W_3)	9	11	18	4	6
Tomato	0	1	17	0	0

[1] Source: Tingey et al. (1973a).

[2] Alfalfa (*Medicago sativa*. L. cv. Vernal), broccoli (*Brassica oleracea botrytis*, L., cv. Calabrese), cabbage (*Brassica oleracea capitata*, L. cv. All Season), radish (*Raphnus sativus*, L. cv. Cherry Belle), tomato *Lycopersicon esculentum*, Mill, cv. Roma VF), and tobacco (*Nicotiana tabacum*, L. cv. Bell W_3). Pinto beans (*Phaseolus vulgaris* L., cv Pinto), oats (*Avena sativa* L., cv. Clintland 64), soybean (*Glycine max* L., Merr., cv. Hark), tobacco (*Nicotiana tabacum* L., cv. Bel W_3).

[3] Source: Tingey et al. (1971a).

[4] Average foliar injury resulting from 0.10 ppm O_3 only was 2% alfala, 7% radish, 40% tobacco, and no foliar injury for the other three species.

[5] Concentrations below either 2 ppm nitrogen dioxide or 0.50 ppm sulfur dioxide alone produced no foliar injury.

[6] Sensitive cultivar.

higher concentrations of NO_2 and SO_2 is not readily explained. This reduced response at higher exposures is unlike that observed for the O_3 and SO_2 mixtures and may be related to stomatal closure, which would reduce pollutant influx into leaves. Although both of these studies reported pronounced synergism at concentrations below the thresholds for single pollutants, some other studies examining plant response to similar pollutant mixtures have not found synergistic effects at levels significantly below the thresholds for the single pollutants (e.g., Bennett et al., 1975; Heagle and Johnson, 1979).

An additional complication arises when assessing controlled exposure studies of pollutant mixtures in that exposure regimes employed are not necessarily representative of those occurring in the ambient environment. For example, peak O_3 concentrations are unlikely to occur simultaneously with peak NO_2 and SO_2 concentrations near combustion sources because NO, which is released along with NO_2, is effective at scavenging O_3.

Table 7-3 summarizes plant responses following long-term exposure to pollutant mixtures. The lack of an effect of SO_2 on soybean yield in the higher exposure regime in the Heagle et al. (1974) study is unexpected in view of the decrease in growth reported by Tingey and coworkers. This may have occurred because different measures of productivity were used and because the measurements were not taken at the same stage of growth. The Red Kidney Bean study was designed to introduce an increment of 0.10 ppm (260 $\mu g/m^3$) SO_2 with 50 percent nonfiltered air in the South Coast Air Basin. Oshima (1978) reports that the O_3 concentrations in the exposure chambers with 50 percent nonfiltered air probably reached 0.15 ppm (294 $\mu g/m^3$), 0.12 (235 $\mu g/m^3$),

TABLE 7-3. CONTROLLED EXPOSURE STUDIES OF LONG-TERM EXPOSURES TO POLLUTANT MIXTURES

Concentration ppm ($\mu g/m^3$)	Exposure Period	Response	Comments	Reference
0.05 (98) O_3+ 0.05 (131) SO_2	8 hrs/day 5 days/week 18 days	Synergistic	Greenhouse grown soybeans displayed reductions in top weight (21%), root fresh (24%) and dry (20%) weights and shoot-root fresh and dry weight ratios. No effect on top dry weight or plant height. Plant growth was not affected by either pollutant alone.	Tingey et al. (1973b)
0.05 (98) O_3+ 0.05 (131) SO_2	8 hrs/day 5 days/week 5 weeks	Additive/ Antagonistic	Greenhouse grown radishes displayed less than additive reductions in plant fresh weight, and root dry weights. Additive reductions were observed for leaf fresh and dry weights. Exposure to either SO_2 or O_3 alone affected plant growth.	Tingey et al. (1971b)
0.10 (262) SO_2+ partially filtered ambient air containing O_3*	6 hrs/day on 45 days over 11 weeks	Synergistic	Approximately a 33% reduction in total seed weight of Red Kidney Bean when compared with ambient air having 50% of the ambient O_3 removed. Plants were grown in pots placed in the field inside special design closed top field chambers.	Oshima (1978)
0.10 (200 O_3+ 0.10 (260) SO_2	6 hrs/day 133 days (continuously)	Additive (No SO_2)	No effect in soybeans from sulfur dioxide alone or combination with O_3 (different from the effects of O_3 alone) plant growth, and foliar injury. Plants were grown in the ground and exposed in closed field chambers.	Heagle et al. (1974)

*See text.

and 0.12 (235 $\mu g/m^3$) ppm on the highest, second highest, and third highest O_3 days, respectively. Exposure regimes reported in the Oshima study would violate the current O_3 standard (0.12 ppm, 1-hour average, not to be exceeded more than once per year, statistical form) and the exposure regime used in the study by Heagle and coworkers probably would have violated the standard.

In summary, short-term and long-term exposure studies of pollutant mixtures provide mixed results that are difficult to interpret. Although these studies indicate that pollutant mixtures can produce effects that are greater than additive (especially at low exposure levels), additional research is needed to resolve reported differences.

iii) Zonal Air Pollution System Exposure Studies

The Zonal Air Pollution System (ZAPS) is a relatively recent development in controlled exposure systems that allows plants to be grown without the use of chambers. The ZAPS system releases controlled amounts of SO_2 from a pipe upwind of the vegetation. Plant response to different exposure levels are examined by placing plants and SO_2 monitors at different distances downwind of the ZAPS release pipe. It is difficult to characterize exposure regimes in ZAPS studies for two reasons:

1) Estimates of plant exposure are subject to uncertainty. The number of monitors are limited and concentrations at each location are not continuously monitored. Furthermore, the close proximity of the vegetation to the release point of SO_2 and variations in meteorological conditions and canopy structure also increase the uncertainties associated with plant exposure (Miller et al., 1980).

2) Other pollutants are not excluded in this exposure system and could, if present, influence plant response.

The most extensive ZAPS SO_2 exposure studies have been conducted by Miller and coworkers. In one study using repeated exposures lasting 4.5 hours, significant reductions in the yield of soybeans ranged from 6.4 percent at 0.09 ppm SO_2 to 45 percent at 0.79 ppm (Sprugel et al., 1980). Although ambient O_3 levels may have exceeded 0.10 ppm on more than one occasion, it is not possible to attribute any effect on soybeans to O_3 exposure alone. Within this study, exposure to 5 different mean SO_2 concentrations between 0.09 (240 $\mu g/m^3$) and 0.36 ppm (940 $\mu g/m^3$) for 18 repeated 4.5 hour exposures reduced yield from 6.4 to 19 percent. No single 3-hour average SO_2 concentration in these studies exceeded 0.5 ppm. The consistency of results over a two year period at different geographical locations supports these findings.

b) Ambient Exposure Studies

Field observations of plant response in agronomic settings and natural ecosystems show that SO_2 exposure can increase foliar injury, decrease plant growth and yield, and decrease the richness and diversity of plants. Ambient exposure studies have three major advantages over controlled exposure studies: 1) plants are exposed and grown under conditions that occur in the ambient air; 2) large sample sizes can be collected; and 3) only field observations can demonstrate long-term changes in plant communities resulting from SO_2 exposures. On the other hand, it is more difficult to define actual exposure conditions (i.e., frequency, concentration, duration), and to ascribe the observed plant responses to SO_2 alone.

i) Short-Term Exposures

The criteria document cites ambient exposure studies. These studies are important because they provide:

1) quantitative estimates of short-term SO_2 exposure and observations of plant response,
2) the only available data on plant responses to short-term exposures in the field observed near point emission sources, and
3) observations on larger numbers of species than would be practical in laboratory settings.

The ambient exposure studies of Dreisinger and McGovern (1970) and McLaughlin and Lee (1974) provide the most extensive observations of foliar injury in the vicinity of major point sources of SO_2 (CD, pp. 8-19 to 8-24). Observations of minimum concentrations required to produce foliar injury in these studies are limited by the number of SO_2 monitors, location of individual plant species, and distribution of SO_2 exposures (i.e., concentration, frequency, exposure duration).

Figure 7-1 shows concentration-response curves for foliar injury that have been developed from observations on a variety of agricultural crops, trees, and native vegetation from the 1970 to 1973 growing seasons. This figure does not represent the percent of foliar injury, but the cumulative percent of affected species (i.e., those species in which some foliar injury was observed in conjunction with air quality measurements) for a given concentration of SO_2. Plotted lines were fitted by eye.

The data shown in Figure 7-1a were collected in the vicinity of a coal fired power plant in the southeastern U.S. from 1970 to 1973. Following review of these data, McLaughlin and Lee concluded that most species in the area "are not visibly affected by sulfur dioxide when

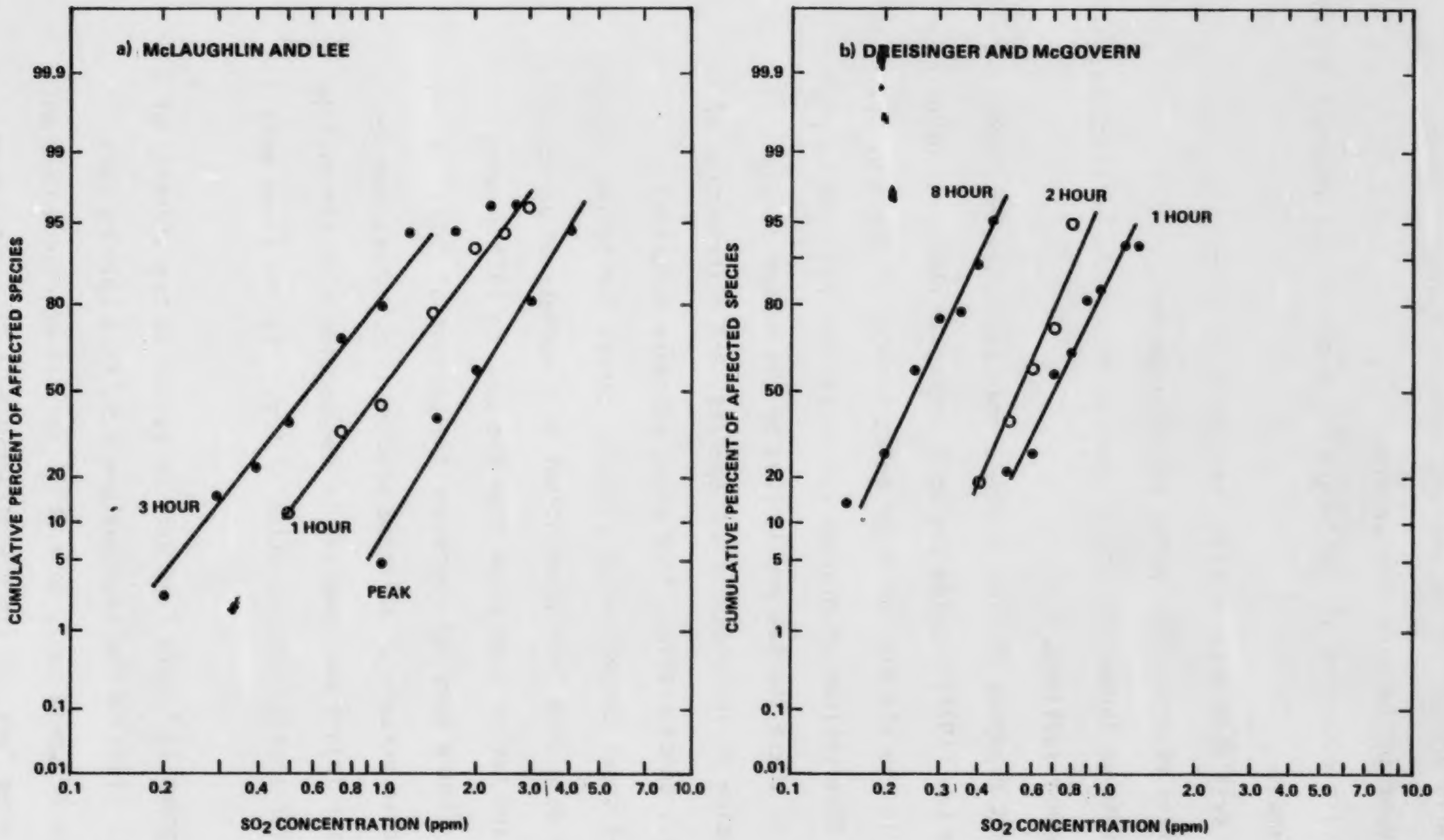

Figure 7-1. Concentration-response relationships for the minimum concentration of SO_2 required to produce foliar injury. a) Derived from 84 species near a coal fired power plant in the southeastern U.S. b) Derived from 37 species situated near a smelter in Canada. Cumulative percentages of species affected (developing foliar injury) at a given concentration are shown. Since all species examined in each study were not exposed during each fumigation, the actual number of plants affected during any one fumigation is less than the cumulative percent shown above.

peak (about a 3-minute average), 1-hour average, and 3-hour average sulfur dioxide concentrations do not exceed 1.0, 0.50 and 0.20 ppm, respectively." Similarily Dreisinger and McGovern concluded that SO_2 concentrations should not exceed 0.70 ppm for 1-hour, 0.40 ppm for 2 hours, 0.26 ppm for 4 hours and 0.18 ppm for 8 hours under relatively sensitive conditions. However, review of their data indicates at least several species developed foliar injury following exposure to concentrations below those reported above.

For both studies, all species were not exposed and injured during any specific fumigation event, and plants were not always in the most sensitive condition during each exposure (e.g., exposures when stomates were open). In the McLaughlin and Lee study, the greatest percentage of affected species following a single exposure is about 20 percent.

The data plotted in Figure 7-1 provide relatively consistent concentration-response relationships indicating that the number of plants showing first signs of foliar injury affected within a given concentration range approximates a normal distribution. The slope of the lines for the Dreisinger and McGovern data appear to be steeper than the slope of the lines for the McLaughlin and Lee data, suggesting that differences in peak to mean SO_2 ratios, plants exposed, and environmental conditions may have affected plant response in different situations. Reports of increased foliar injury when peak to mean ratios are high suggest that peak rather than mean concentrations are probably of greatest importance. Dreisinger and McGovern report that plants are most sensitive during periods of warm, humid weather that are favorable for plant growth.

Several limitations that should be considered when evaluating these data are listed below.

1) Although these plots show that the concentration required to produce foliar injury decreases with increasing duration, it is not possible to establish definitively which averaging period is best linked to the production of foliar injury.

2) It is not possible from these data to derive specific estimates of the amount of leaf surface affected or reductions in growth and yield for individual species.

3) The data shown in Figure 7-1 have only incorporated results from species that were affected by known SO_2 concentrations. In the McLaughlin and Lee study SO_2 related foliar injury was observed in a total of 196 species over a 20 year period. No foliar injury was reported in 23 additional species. Figure 7-1 does not reflect data on the other plants affected by SO_2 in the McLaughlin and Lee study because the specific SO_2 exposures listed are only associated with 84 of the 196 affected species. Of a total of 39 species observed in the Dreisinger and McGovern study, only 2 species exhibited no foliar injury at the observed concentrations.

ii) Long-Term Exposures

Most field studies of long-term SO_2 exposures have focused on natural ecosystems. Unlike short-term exposures studies, observational studies of long-term SO_2 exposure typically focus on different biological endpoints including the richness and diversity of species in an area, seedling survival, premature leaf drop, and reduced growth (Linzon, 1978; Rosenberg et al., 1979; Winner and Bewley, 1978a,b).

Although the importance of short-term peaks relative to long-term averages in producing effects remains unclear, observational studies provide strong support that long-term SO_2 exposures can affect the diversity and richness of species. A study of species composition in the vicinity of a 25-year old coal fired power plant demonstrates reductions in the number of vascular* plant per unit area and species diversity (Rosenberg et al., 1979). Similarly, Winner and Bewley (1978a,b) report that both vascular plants and mosses show a marked increase in understory species diversity with increasing distance from the source. The criteria document notes "changes in moss communities were conspicuous and included decreasing values for moss canopy coverage, moss carpet depth, dry weight, capsule number, and for the frequency of physiologically active versus inactive moss plants" (CD, p. 8-47).

Table 7-4 summarizes results of long-term ambient SO_2 exposures. A difficulty in interpreting long-term ambient exposure studies is determining whether short-term peaks or long-term concentrations are most closely associated with the effects observed. In the Canadian studies on White Pine, Linzon indicates that the maximum 30 minute SO_2 concentrations are estimated to be about 2.5 ppm at the West Bay site and 1.0 ppm at the Portage Bay site. Since concentrations even below these levels may cause foliar injury and other effects following short-term exposures, the effects observed at the West Bay site may be associated with repeated peak rather than long-term low-level exposures. However, both the author of the study and the criteria document associate the effects observed with long-term exposure average concentrations of 0.045 ppm SO_2 for the West Bay site and 0.017 ppm SO_2

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*Vascular plants (e.g., agricultural crops, trees, shrubs) are characterized by a vascular system that is used in the movement of water and other materials to different parts of the plant. Conversely, non-vascular plants (e.g., lichens, mosses) lack a vascular system.

TABLE 7-4. FIELD STUDIES OF CHRONIC AMBIENT SO_2 EXPOSURES

Source/Location	Exposure, ppm (Duration)	Effects	References
Vascular Plants:			
Nickel-Copper Smelters/ Sudbury District Ontario, Canada (study on White Pine)			
West Bay (19 miles N.E.)	0.045* (10 year average)	1.3% reduction in net tree volume and a 2.6% annual average mortality rate, foliar injury was observed on foliage from both the current year and previous years.	Linzon (1971, 1978)
Portage Bay (25 miles N.E.)	0.017* (10 year average)	0.5% loss in net tree volume and a 2.5% annual average mortality rate, foliar injury on current year needles developed slowly and injury from the previous year was apparent.	
Grassy to Emerald Lake (40-43 miles N.E.)	0.008* (10 year average)	A 1.8% increase in net annual tree volume and a 1.4% annual average mortality rate, little foliar injury was apparent.	
Lake Matimenda (93 miles W)	0.001 (5 month growth season-1971) control for above	A 2.1% increase in net annual tree volume and a 0.5% annual average mortality rate.	
Non-Vascular Plants:			
Coal Fired Power Plant/ Ohio	0.020 (Annual Average)	Two lichen species absent. The distribution of more resistant became apparent at annual average concentrations of 0.025 ppm SO_2.	Showman (1975)
Industrial Pollution/ England and Wales		% reduction in the number of tolerant lichen epiphytes:	Hawksworth and Rose (1970) LeBlanc and Rao (1975)
	0.03 to 0.06	95	
	0.02 to 0.03	62	
	0.01 to 0.02	24	
	0.005 to 0.01	13	
	<0.005	0	
	(Annual Averages)		

*Exposures probably included some heavy metals (e.g., As, Cu) that are found in smelter emissions (Chapter 4).

for the Portage Bay site. As shown in Table 7-4, Linzon (1978) indicates that there are differences in the effects observed as distances are increased from the smelter and thus, peak concentrations are reduced. The nature of the effects observed suggests that they may be associated with either continuous or repeated peak SO_2 exposures (Linzon, 1978). The presence of metals may have affected plant response or sensitivity in this study.

Long-term ambient exposure studies show that the community composition of non-vascular plants* can be affected by exposure to long-term low-levels of SO_2. Results of these studies are summarized in Table 7-4. Similarly, non-vascular plants are also reported to have responded to long-term SO_2 levels between 0.005 and 0.03 ppm near Sudbury, Canada (LeBlanc and Rao, 1975). In contrast to vascular plants, there are several reasons that non-vascular plants are more sensitive to SO_2 and that long-term and not short-term exposures are probably associated with the effects observed at low long-term SO_2 exposure levels, including:

1) Sulfur metabolites cannot be eliminated through translocation (Nieboer et al., 1976). Lichen mapping studies have repeatedly shown associations between changes in plant communities and the accumulation of sulfur metabolites (CD, p. 8-53).
2) Pollutants cannot be excluded during periods of high pollutant levels because they lack both epidermis and stomata (Nieboer et al., 1976).
3) Non-vascular plants probably have less buffering capacity than vascular plants (Nieboer et al., 1976).

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*See footnote on page 105.

For these reasons, non-vascular plant communities appear to be more sensitive to long-term low-level SO_2 exposures than vascular plants. Although investigators have associated effects in lichens with long-term low-level exposures, the relative importance of repeated pollution episodes as compared with continuous exposure to low SO_2 levels cannot be determined at this time.

Non-vascular plants vary widely in their distribution across the U.S. and serve a variety of functions in a number of different environments from the desert to coniferous forests. Non-vascular plants affect survival of other plant species (CD, pp. 7-9 to 7-13). In some areas, non-vascular plants participate in the process of soil formation, prevent erosion, play a role in succession, and can be an important food source for foraging animals when other vegetation is scarce (Linzon, 1978; Winner et al., 1978). Non-vascular plants can also play an important role in influencing the movement of materials within the ecosystem. For example, lichens fix 5 to 20 percent of the total nitrogen requirement (2 to 11 kg nitrogen/ha) for Douglas fir, the dominant producer in northwestern coniferous forests (Denison, 1973).

3. Staff Recommendations

SO_2 induced damage to commercial crops, cultivated ornamentals and marked changes in natural ecosystems clearly may affect public welfare. If the recommended ranges of the primary standards do not provide adequate protection, the staff recommends consideration of vegetation effects in evaluating the need for both short- and long-term secondary standards.

a) Short-Term Exposures

Controlled exposure and field observation studies of the responses of vascular plants to SO_2 exposure provide support for continuation of a short-term standard to protect vegetation. These studies show a progression of effects following SO_2 exposure from physiological and biochemical changes to foliar injury and decreases in growth and yield. The original 3-hour SO_2 standard (0.50 ppm), promulgated in 1970, is apparently based on foliar injury in Mountain Ash following a single controlled exposure to 0.54 ppm (1400 $\mu g/m^3$) (DHEW, 1970). This standard was maintained in 1973 following a review of the secondary SO_2 standards where additional foliar injury data provided added support for plant injury to SO_2 exposure (38 FR 25678; EPA, 1973).

Available evidence shows that plant responses vary with both concentration and time. Controlled exposure studies examining plant response to SO_2 show that concentration is generally more important in the production of plant responses which emphasizes the importance of peak exposures (CD, p. 8-15; McLaughlin et al., 1979). However, as exposure periods are extended, concentrations required to produce effects diminish. Comparison of levels associated with plant injury and ambient variations in SO_2 concentrations with time indicate levels that are reported to injure vegetation are only expected in the vicinity of point sources. The occurrence of peak SO_2 levels between mid-morning and early afternoon, a time when stomates are typically open, increases the likelihood that plants will be injured by ambient fumigations near point sources. Because meteorological conditions and emission rates vary with time, maximum SO_2 concentrations producing effects following short-term exposures should be associated with short-term fumigation periods from less than an hour up to several hours. Controlled exposure studies (Table 7-5) demonstrate that plants can be affected by SO_2 exposure for 2 to 4 hours. Thus an averaging period of 3 hours would be a reasonable choice.

The level of a revised standard would depend on the extent to which anticipated effects would be considered to be adverse. ZAPS field studies on soybeans suggest multiple peak SO_2 exposures that do not exceed the level of the current 3-hour secondary standard can result in reduced growth and yield. Although few controlled exposure studies at low exposure regimes have been performed to date, these studies indicate that single exposures that would not violate the current SO_2 standard can increase foliar injury (See Table 7-5) and affect growth and yield (i.e., 2 hours at 0.5 ppm). Foliar injury data from ambient exposure studies show greater continuity of response concentrations because of the larger number of observations. The concentrations associated with foliar injury for the ambient exposure studies in Table 7-5 were derived from the observations plotted in Figure 7-1. In each case, the concentration associated with foliar injury corresponds with the concentration associated with producing foliar injury in about 20 percent of the species affected. Although foliar injury may be caused by natural phenomena (e.g., insect damage, unfavorable weather, and nutrient stress), increases in foliar injury reduces the aesthetic value of natural vegetation and ornamental plants, as well as, the commercial value of some leafy agricultural crops (e.g., spinach).

While the acute studies by Tingey and co-workers (1971a,b) on pollutant mixtures of SO_2, NO_2, and O_3 suggest that exposures below current standard levels may affect foliar injury, the results of these studies do not agree with some other work reporting that foliar injury occurs only at higher concentrations (e.g., Bennett et al., 1975; Heagle and Johnson, 1979). Ambient exposure studies near point sources shown in Figure 7-1, where mixtures of NO_2 and O_3 might be expected to be

TABLE 7-5. STAFF ASSESSMENT OF SHORT-TERM VEGETATION STUDIES

Averaging Period	Controlled Exposure Results[1]	Ambient Exposure Results[2]
1-Hour	-	0.50 ppm - 20% Foliar Injury
2-Hour	0.25 ppm - Foliar Injury 0.50 ppm - Reduced Growth and Productivity	0.40 ppm - 20% Foliar Injury
3-Hour	-	0.32 ppm - 20% Foliar Injury
4-Hour	0.40 ppm - Foliar Injury	-

[1] Derived from Adedipe et al. (1972), Berry (1971, 1974), Jacobson and Colavito, (1976) and Heck and Dunning (1979). All results from single exposures at stated level and averaging time (See Table 7-1).

[2] Derived from Dreisinger and McGovern (1970) and McLaughlin and Lee (1974). Values provided in this column are for concentrations that are associated with foliar injury following a single exposure. Values shown have been interpolated from Figure 7-1.

present with SO_2 in low ambient concentrations, suggest that plant response is not much different from the response that would be expected for SO_2 exposure alone. In essence, these data do not readily support a combination standard at this time.

Based on the available data, a 3-hour secondary standard at or below the level of the current standard may be needed to protect vegetation. A range of 0.4 to 0.5 ppm (1050 to 1300 $\mu g/m^3$) would be roughly equivalent to the lowest reported exposure regime affecting growth and productivity. Such a standard would not be expected to prevent against all foliar injury but should protect over half of exposed species against foliar injury even during "sensitive" exposure periods. Available air quality information indicates that such concentrations would only be expected to occur in the immediate vicinity of point sources (Burton et al., 1982; Frank and Thrall, 1982). Although cultivated crops may be equally sensitive in different regions if plant water status is not stressed, natural ecosystems would be expected to be less sensitive in arid regions (e.g., southwestern U.S.) where soil moisture and relative humidity tend to be lower. Given the available information, 1-hour standards in the middle and lower portions of the range of interest for a primary standard (0.25 to 0.75 ppm) may provide equivalent or better protection for vegetation than the current 3-hour standard; in this case, the secondary standard may be set equivalent to the primary standard. In the absence of a primary standard that provides adequate protection the staff recommends a 3-hour secondary standard.

b) Long-Term Exposures

Available evidence suggests that long-term exposure to SO_2 may affect foliar injury, growth, productivity, and the numbers and density of species present in plant communities.

Studies on the effects of vascular plants suggest that long-term exposures may reduce productivity, cause premature leaf drop, and otherwise affect plants. Although the investigations by Tingey and co-workers (1971b) and Keller (1978, 1980) suggest decreases in measures of productivity following exposure to 0.05 ppm (131 $\mu g/m^3$) SO_2, other studies have not reported similar effects until slightly higher levels. Several ambient exposure studies examining effects on vascular plants have effectively demonstrated changes in species richness and diversity, but do not provide specific levels that can be associated with such changes (e.g., Rosenberg et al., 1979). However, reductions in tree volume and increased mortality in White Pine have been associated with 10 year average SO_2 concentrations as low as 0.017 ppm (45 $\mu g/m^3$). Nevertheless, it is unclear if these effects were most clearly associated with repeated peak or the long-term average exposures (CD, p. 8-19). The presence of metals may have affected plant response in this study. The reported damage at the Portage Bay site showed little injury associated with acute exposure. Moreover, peak half hour concentrations (< 1 ppm, 2600 $\mu g/m^3$) reported by Linzon near the Portage Bay site indicate that the second highest 3-hour concentration probably did not exceed the current secondary standard level of 0.5 ppm (1300 $\mu g/m^3$). Thus, it is unlikely that effects observed in this study can be attributed to a short-term exposure. Although these data suggest that long-term SO_2 levels may affect vascular plants, the data are not well enough developed to provide the principal basis for selecting a level for a long-term secondary standard but do suggest the need to limit long-term SO_2 levels.

Mapping studies of non-vascular plant responses provide convincing evidence that non-vascular plants may be affected by SO_2 at low levels. Although non-vascular plants display both visible injury and changes in community composition, available studies suggest that species diversity appears to be the most sensitive index of non-vascular plant response (LeBlanc and Rao, 1975). As Table 7-4 shows, non-vascular plants may be injured by exposure to annual arithmetic mean concentrations of SO_2 from as low as 0.005 ppm (13 $\mu g/m^3$) to about 0.06 ppm (160 $\mu g/m^3$); the later concentration can eliminate most species of epiphitic lichens (LeBlanc and Rao, 1975).

If the data of Mueller et al. (1980) (See Figure 4-2) are indeed representative of regional SO_2 levels in the northeast quadrant, then existing studies suggest that current non-urban SO_2 levels may have effects on the richness and diversity of non-vascular plants primarily in the northeast where rainfall, relative humidity, and soil moisture are relatively high. Assuming that the deposition and accumulation of sulfur in non-vascular plants is an important parameter that affects plant response, the deposition of SO_2 (northeast seasonal concentrations of $\sim$ 25 to 50 $\mu g/m^3$) may be even more important than sulfate (northeast seasonal concentrations of $\sim$ 6 to 12 $\mu g/m^3$) deposition in determining the response of non-vascular plants to sulfur oxides. To the extent that the contribution of non-vascular plants to the stability and productivity is considered to be important, reductions in regional SO_2

levels in the northeast may be warranted. Other uncertainties in the exposure-response relationships of non-vascular plants that should be recognized include:

1) Since many non-vascular plants live deep within the canopy of their environment, current monitoring efforts may overestimate actual concentrations experienced by non-vascular plants.
2) Although existing studies associate effects with long-term averages and indicate that the mechanism of toxicity is associated with accumulation of sulfur in tissues, the importance of repeated episodes on plant response cannot be eliminated at this time.

Since regional loadings of atmospheric sulfur is a problem that will be addressed during future actions on visibility (EPA, 1982b) and acidic deposition, the staff recommends that any action on the regional effects of SO_2 on non-vascular plants be deferred until that time.

B. Materials Damage

1. Nature of Effects

SO_2 alone or in conjunction with hygroscopic and other active components of particulate matter contributes to the physical damage of a wide range of materials. SO_2 has been associated with the corrosion of ferrous and non-ferrous metals, degradation of zinc and other protective coatings, and with the deterioration of inorganic building materials (e.g., concrete and limestone), as well as paper, leather goods, works of historical interest, and certain textiles. SO_2 is corrosive in the presence of moisture because of its electrolytic properties that enhance electrochemical corrosion and because of its acidity. In addition to moisture, other factors that affect the extent of SO_2 induced damage include temperature, sunlight, wind speed, protective measures taken, as well as the level of SO_2 to which the material is exposed.

Sulfur dioxide-induced materials damage becomes economically significant, and thus is most likely to affect public welfare only when one or more of the following conditions are met:

1) the service life of the material is impaired or prematurely ended;
2) the frequency of maintenance tasks must be increased; or
3) the quantity or quality of the service rendered by the affected object is diminished (Gillette, 1975).

As discussed in the criteria document (CD, Chapter 10), the evidence on the effects of SO_2 on materials is drawn from field and laboratory studies. In addition, estimates of the economic loss associated with SO_2 damage have been made. The key findings from these assessments are presented below:

1) The evidence presented in the criteria document clearly establishes that SO_2 (at humidities commonly exceeded in large regions of the U.S.) can accelerate the corrosion of exposed ferrous metals (Upham 1967; Haynie and Upham, 1971; Haynie and Upham, 1974). With the exception of weathering steel, these findings have little practical significance however, since ferrous metals are normally protected by paint, zinc, or by addition of alloys when exposed outdoors. Such measures reduce corrosion and in the case of paints enhance the aesthetic appearance of materials. Certain non-ferrous metals such as aluminum and copper, however, are relatively unaffected by levels of SO_2 currently observed in the ambient air (Fink et al., 1971; Abe et al., 1971).
2) Both field and laboratory studies have shown that zinc corrosion is accelerated by SO_2 and that time of wetness, SO_2 concentration, and surface geometry are determining factors (Guttman, 1968; Haynie et

al., 1976; Haynie, 1980). Such findings are potentially significant because of the use of zinc as protective coatings for ferrous metals.

3) Controlled exposure chamber studies by Campbell et al. (1974) and Spence et al. (1975) have examined the effects of SO_2 on several exterior paints. The results from these studies suggest that coatings, which do not contain aluminum or magnesium silicates or calcium carbonate or combinations thereof, are relatively unaffected by SO_2 at concentrations up to 1.0 ppm after exposure periods of 400, 700, and 1000 hours. For an oil base house paint which contained magnesium silicate, Spence et al. (1975) reported statistically significant errosion at 0.03 ppm SO_2 after exposure periods of nominally 250, 500 and 1000 hours which they attributed to the effects of SO_2 and relative humidity. Unfortunately, their exposure study of acrylic latex house paint had to be terminated before completion of the exposure cycle. As a result, data on this widely used coating are not available at SO_2 concentrations (< 1.0 ppm) that are more relevant to current ambient conditions. The investigators cautioned that their findings for one coating should not be generalized to an entire class of paints because of differences in paint formulations.

4) The studies cited in the criteria document (CD, pp. 10-34 to 10-37) primarily show that SO_2 can react with calcareous materials and, thus, cause deterioration of inorganic materials such as concrete, marble, and limestone used in buildings, monuments, and some statuary. These studies have not fully investigated the relative

contribution of SO_2 as compared to other components of acidic deposition (wet and dry) as well as other physical and biological agents.

5) The studies of the effects of SO_2 on textile, leather and paper goods are less relevant since these materials are not typically exposed for long periods in the ambient environment. The preservation of documents and old books is, however, of concern to libraries and museums (CD, p. 10-37).

6) The criteria document concludes that the dollar value of SO_2 associated material damage in 1970 ranged from $450 million to $1.4 billion in 1978 dollars. It was also estimated that the reduction in the average annual SO_2 ambient levels in U.S. urban areas from 1970 to 1978 resulted in a total U.S. annual benefit for 1978 of approximately $0.4 billion dollars (CD, p. 10-71). These estimates, however, must be viewed with caution since they provide only a crude indication of the costs associated with SO_2 materials damage. Some of the limitations inherent in the underlying estimates include:

   a) the lack of reliable damage functions for the full range of materials that may be affected by SO_2;

   b) uncertainty as to quantities and distribution of materials in place, and the level of SO_2 as well as the environmental conditions (i.e., relative humidity) to which they may have been exposed;

   c) uncertainty as to whether the useful life of the materials was actually impaired; and

   d) inadequate consideration of substitution possibilities.

2. Mechanisms and Quantitative Relationships

Of the materials potentially affected by SO_2, the most accurate damage functions have been developed for zinc coated materials. Based on these functions, it is possible to relate the corrosion of zinc to varying concentrations of SO_2 under different environmental conditions. SO_2 induced damage to zinc coatings may also be economically significant because zinc is used as a coating for ferrous metals that are to be exposed in the ambient air. Haynie (1974) attributed 90 percent of the Fink et al. (1971) nationwide estimate of exterior metal corrosion costs (some $1.4 billion) to the corrosion of galvanized (zinc coated) steel. On the other hand, Stankunas et al. (1981) in their survey of Boston, Massachusetts, found far less than the average per capita amount of bare galvanized metal exposed. They reported an annual cost due to SO_2 corrosion of only $335,000 for the Boston metropolitan area. No attempt was made to extrapolate this to a national estimate. They attributed their findings to development of new coatings that adhere to galvanized metals and which are aesthetically more pleasing and afford additional protection.

Zinc is anodic with respect to steel and, thus, when zinc and steel are in contact with an electrolyte, the electrolytic cell provides current to protect the steel from corrosion while some oxidation of the zinc occurs (CD, p. 10-23). In addition, zinc naturally forms a protective film of zinc carbonate which reduces the rate of corrosion. SO_2 or other acidic gases, in the presence of moisture, however, destroys or prevents the film from forming, thus resulting in the acceleration of the corrosion process.

Reporting on the work of a number of investigators, the criteria document identified several factors that influence the corrosion rate of zinc coated materials. These include: the time the material surface is wet, SO_2 concentration, wind speed, and geometry of the exposed surface. The latter factor controls delivery of SO_2 to the material surface and, in part, explains why certain surfaces such as zinc coated chain link fences exhibit higher corrosion rates than zinc coated siding and roofing materials.

Haynie (1980) incorporated these factors into the following mathematical expression to determine the corrosion rate for galvanized materials (zinc coated) under various conditions:

$$C_z = 2.32\, t_w + 0.0134\, V^{0.781}\, (SO_2)\, t_w, \text{ for small sheets} \qquad (7\text{-}1)$$

$$C_z = 2.32\, t_w + 0.0082\, V^{0.781}\, (SO_2)\, t_w, \text{ for large sheets} \qquad (7\text{-}2)$$

$$C_z = 2.32\, t_w + 0.0183\, V^{0.781}\, (SO_2)\, t_w, \text{ for wire fence} \qquad (7\text{-}3)$$

where:

C_z = corrosion (μm)

t_w = time of wetness (years)

V = wind velocity (m/s)

SO_2 = sulfur dioxide concentration (μg/m^3)

To determine the time of wetness when the average relative humidity is known, Haynie, 1980 developed the following relationship:

$$f = \frac{(1-k)\, RH}{100-k\, (RH)} \qquad (7\text{-}4)$$

where:

f = fraction of time relative humidity exceeds the critical value (90% for zinc sulfate)

RH = average relative humidity

k = an empirical constant less than unity ($k = 0.86$)

Based on equations 7-2, 7-3, and 7-4, the annual rate of corrosion for zinc coated roofing, siding, and wire fence can be plotted as shown in Figures 7-2 and 7-3. This assumes a typical relative humidity of 70% for inland areas east of the Mississippi River, 80% for the seacoast, and 30% for desert areas as in California and Arizona. Under these conditions, the fractional time of wetness is 0.25 for inland eastern states, 0.35 for the seacoast, and 0.057 for desert areas. A typical wind speed of 4 meters per second (9 mph) was used.

It is evident from Figures 7-2 and 7-3 that relative humidity as well as SO_2 can significantly effect the corrosion of zinc coated materials. This must be considered in estimating potential nationwide damages to these materials.

An additional consideration in making such estimates is whether the service life of the zinc coated material have been impaired or prematurely ended. This is a function of the coating thickness and prevailing maintenance practice. Gillette (1975) reported that coating thickness varies with intended use, ranging from 26 μm for building accessories and wire fencing to 85 μm for pole line hardware. The work of Bird (1977) and Haynie (1980), however, suggest coating thickness on a given piece of material can vary as much as ± 40 percent. For wire fencing, the product expected to be most sensitive to corrosion, this means the first rust could occur after 16 μm of corrosion. Using Figure 7-3, it can be estimated that first rust may occur in wire fencing after 10, 13, or 17 years of exposure at 70 percent relative humidity and long-term mean SO_2 concentrations of 0.03, 0.02, and 0.01 ppm (80, 50, 25 $\mu g/m^3$), respectively. In the absence of SO_2, first rust would not occur until 28 years of exposure at 70 percent relative humidity. Thus, it can be concluded that SO_2-related damage for this material can occur

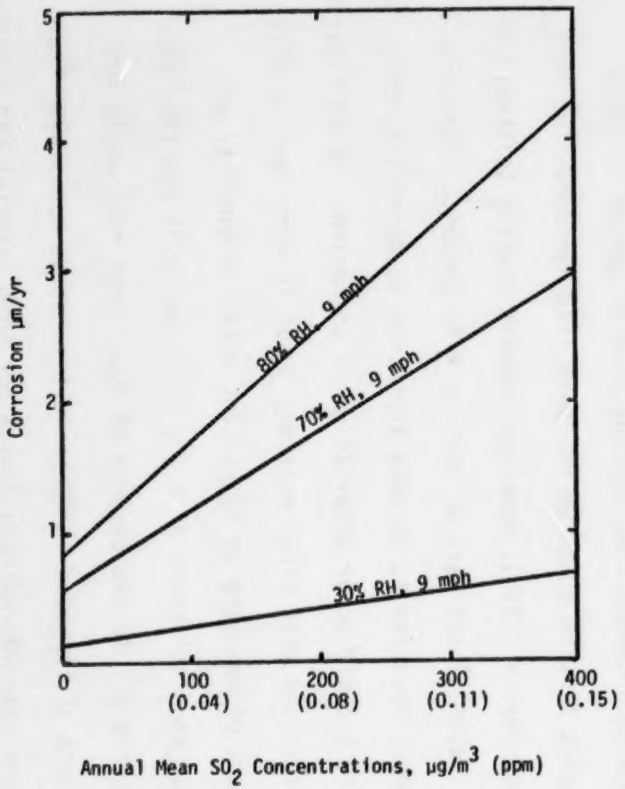

Figure 7-2. Corrosion Rate for Roofing and Siding (Large Sheets). Relationships based on Equations 7-2 and 7-4 (Haynie, 1980).

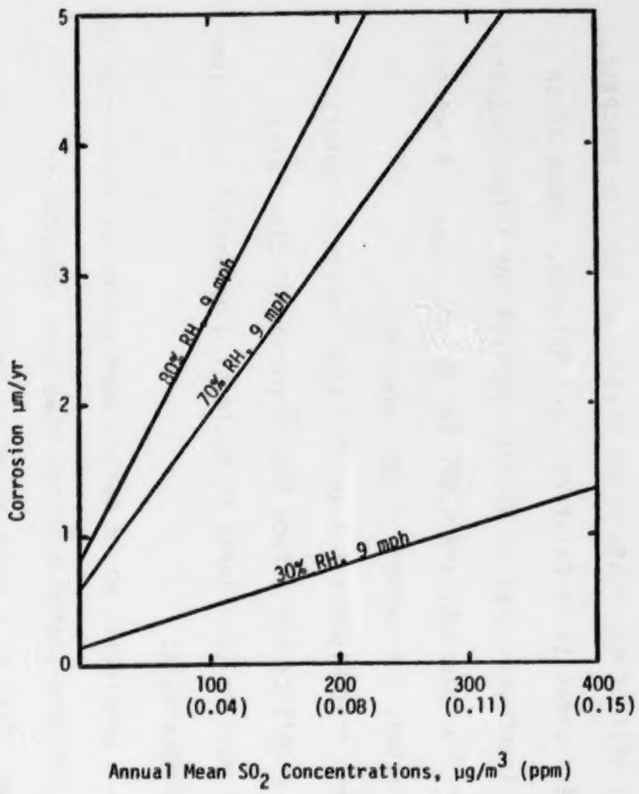

Figure 7-3. Corrosion Rate for Wire Fencing. Relationships based on Equations 7-3 and 7-4 (Haynie, 1980).

down to and at background SO_2 concentrations found in the eastern United States. For other zinc coated products, with different surface geometries and/or coating thicknesses, the time period required for first rust will be longer.

Depending on the prevailing maintenance practices, the material could be painted when rust first appears to provide extended protection or be allowed to deteriorate further until the substrate is damaged to the point that replacement is necessary. Both approaches are commonly employed (Stankunas et al., 1981). This uncertainty with respect to response coupled with the absence of accurate determinations of the amount of materials actually exposed under varying conditions has precluded development of complete and accurate national cost estimates. The work of Stankunas et al. (1981), however, suggests that such costs may be significant assuming other major metropolitan areas in the country experience similar costs ($335,000 per year) as estimated for Boston. The 1976 annual SO_2 values in Boston ranged from 15 to 48 $\mu g/m^3$ (Stankunas et al., 1980).

3. Staff Recommendations

The association of SO_2 with damage to a number of materials suggests that economically important impacts may result at elevated long-term SO_2 concentrations. Control strategies have resulted in marked improvements in long-term SO_2 levels over the past 13 years, which the criteria document associates with substantial benefits (CD, pp. 5-16, 10-71). While the available data are limited and do not permit definitive findings with respect to the potential costs or provide clear quantitative relationships for the full range of potentially affected materials, they generally support the need for limiting long-term SO_2 concentrations in urban areas.

Analysis of existing air quality data (Frank and Thrall, 1982) suggests that without a primary annual standard long-term urban air quality could deteriorate and in a number of large urban areas might exceed the current annual standard. Therefore, consideration should be given to a long-term secondary SO_2 standard at or below the level of the current annual primary standard of 0.03 ppm (80 $\mu g/m^3$) to protect against materials damage effects.

C. Personal Comfort and Well-Being

1. Description of Effects, Quantitative Data

In addition to the health effects discussed in Sections V-B, short-term exposures to SO_2 may also be associated with other perceived responses that may not be related to health; examples include odor perception, eye, nose, or throat irritation, and other non-respiratory sensory responses. As summarized in Section V-B.1, the available data indicate that SO_2 is not detected by human senses at levels below 1 ppm except under controlled conditions that either tend to underestimate the threshold of detection, or use indicators of unknown relevance to personal comfort and well-being (e.g., brain alpha rhythms, eye sensitivity to light).

A number of investigators have noted subjective perceptions of irritative or painful effects such as eye, nose, or throat irritation and cough associated with short-term SO_2 exposures above 5 ppm (Lehmann, 1893; Yamada, 1905; Greenwald, 1954; Amdur et al., 1953) and as low as 0.5 ppm among asthmatics (Kirkpatrick et al., 1982). Healthy subjects exposed for 6 hours to SO_2 had a "threshold of discomfort" at 1 ppm (Andersen et al., 1974). The addition of 2 mg/m^3 "inert" plastic dust to this SO_2 level increased the level of discomfort and the incidence of throat and nose irritation (Andersen et al., 1981). Symptoms such as wheezing and shortness of breath have been observed among asthmatics after short-term exposures to 0.5 ppm SO_2 (Table 5-1). These symptoms are clearly indications of personal discomfort but they are accompanied by substantial functional responses and are of apparent relevance to health (CD, p. 13-51). As such they are not considered here.

2. Staff Recommendations

Because the effects relevant solely to personal comfort and well-being are generally associated with short-term SO_2 levels above the range of interest for the primary standard (0.25-0.75 ppm), there is no support for a secondary standard based on personal comfort and well-being.

D. Acidic Deposition

On August 20-21, 1981, the Clean Air Scientific Advisory Committee (CASAC) concluded that the issue of acidic deposition was so complex and important that a significantly expanded and separate document would be necessary if NAAQS were to be selected as a regulatory mechanism for control of acidic deposition. CASAC noted that a fundamental problem of addresing acidic deposition in a criteria document is that it is produced by several pollutants (including oxides of nitrogen, oxides of sulfur, and acidic fine particles). Consequently, a document on acidic deposition would include various pollutants contributing to wet and dry deposition. The Committee also recommended that a revised version of the acidic deposition chapter be retained in the particulate matter/sulfur oxides and nitrogen oxides criteria documents. In response to these recommendations, EPA is in the process of developing an acidic deposition document that will provide a more comprehensive treatment of this subject. Thus, the issue will not be addressed directly in this staff paper.

E. Summary of Staff Conclusions and Recommendations

Major staff conclusions and recommendations with respect to secondary standards (Section VII.A-D) are summarized below:

1) a) Damage to vegetation by SO_2 resulting in economic losses in commercial crops, aesthetic damage to cultivated trees, shrubs and other ornamentals, and reductions in productivity, species richness and diversity in natural ecosystems constitute effects on public welfare in impacted areas. Such effects are associated with both short-term (minutes to hours) and long-term (weeks to years) exposures to SO_2.

b) Given the available data on the acute effects of SO_2 on plants (growth and yield and foliar injury), a 3-hour standard at or below the level of the current secondary standard (0.5 ppm) may be needed to protect vegetation. If a 1-hour primary standard is chosen that provides equivalent or better protection, then the averaging time and level of the secondary standard can be made equal to the primary standard. In the absence of a primary standard that provides adequate protection for vegetation, a 3-hour secondary standard is recommended.

c) Available data on the effects of long-term SO_2 exposures of vascular plants (e.g., trees, shrubs) suggest the possibility of changes in species richness and diversity, reduced growth over extended periods, and premature needle drop. However, these data are weak and not developed well enough to provide the principal basis for selecting the level of a long-term SO_2 standard. Thus, existing information cannot be used to show significant effects at annual SO_2 levels below the current primary annual standard, but does support the need to protect against the effects of prolonged SO_2 exposure by limiting long-term SO_2 concentrations much above this level.

d) Current long-term SO_2 concentrations over large areas of the northeast exceed levels that may be associated with effects on non-vascular plants (e.g., lichens, mosses). Given uncertainties regarding the extent and importance of these potential effects on natural ecosystems and the regional character of the exposures, the staff recommends that the effects of SO_2 on non-vascular plants be considered in the larger context of regional acidic deposition - visibility - fine particle strategies. As such, no separate long-term secondary standard for non-vascular plants is recommended at this time.

2) a) Elevated long-term SO_2 concentrations in the presence of moisture can damage a number of materials including: exposed metals, paints, building materials, statuary, paper, leather, and textiles. Control strategies have resulted in marked improvements in long-term SO_2 levels over the past 13 years, which the criteria document associates with substantial benefits. While the available data are limited and do not permit definitive findings with respect to the potential costs of SO_2 related material damage or provide clear quantitative relationships for the full range of potentially

affected materials, they generally support the need for limiting long-term SO_2 concentrations in urban areas.

b) Analysis of existing air quality data suggests that without the primary annual standard, long-term urban air quality could deteriorate and in a number of large urban areas might exceed the current annual standard. Therefore, consideration should be given to a long-term secondary SO_2 standard at or below the level of the current annual primary standard of 0.03 ppm (80 $\mu g/m^3$) to protect against material damage effects.

3) The staff concludes that a secondary SO_2 standard is not needed to protect against effects on personal comfort and well-being.

4) The available scientific information indicates that the current 3-hour and annual standards provide reasonable protection against the direct welfare effects associated with ambient SO_2 in general. In essence, the data support maintenance of SO_2 standards at or below levels of the current standards.

5) The acidic deposition issue will not be addressed directly in the review of the sulfur oxides standards.

APPENDIX A. FACTORS THAT INFLUENCE PENETRATION AND DEPOSITION OF SO_2 AND MECHANISMS OF TOXICITY

This material briefly summarizes subject-related and environmental factors that affect penetration and deposition of SO_2, and mechanisms of toxicity. This material supports the discussion in Section V.A. of this paper.

A. Inhalation Patterns

SO_2 (1 to 50 ppm) is almost completely absorbed ($\geq$ 99%) by the nasal passages under resting conditions in both man and laboratory animals (Frank et al., 1969; Speizer and Frank, 1966b; Andersen et al., 1974; Brain, 1970). One study in rabbits also found nearly complete nasal absorption (95-99%) for 10 to 100 ppm SO_2, but reported a decrease in nasal removal to as little as 40% at lower SO_2 levels (0.1 ppm) (Strandberg, 1964). The reason for the apparent difference in absorption rate at 0.1 ppm SO_2 is not clear, although methodological difficulties may have influenced the results. Comparable measurements (< 0.1 ppm) have not been made in humans, but the criteria document concludes that nasal removal at lower SO_2 levels should be similar to that at $\geq$ 1 ppm (CD, p. 1-54).

Subject-related factors that can increase penetration of SO_2 over that observed for quiescent nasal breathing include mouth and oronasal breathing and increased ventilation rates. Forced mouth breathing has been shown to increase SO_2 penetration significantly in animals (Frank et al., 1969). Although direct measurements of SO_2 penetration for mouth or oronasal breathing are not available in humans, measurements of increases in expired SO_2 (Melville, 1970) and bronchoconstriction (Speizer and Frank, 1966a; Melville, 1970; Snell and Luchsinger, 1969) for mouth only versus nasal breathing provide strong indirect evidence of increased penetration with oral breathing through a mouthpiece with the nose occluded. In these studies, the increased bronchoconstrictive responses for resting oral versus nasal exposure are most marked at high concentrations (15 to 28 ppm), and not always statistically significant at lower levels (0.5 to 10 ppm). Comparisons between mouthpiece and nasal or oronasal breathing in exercising asthmatics (0.5 ppm SO_2) indicate that bronchoconstriction increases when going from nasal to oronasal to mouthpiece breathing (Kirkpatrick et al., 1982; Linn et al., 1982a,b). These results indicate a parallel increase in SO_2 penetration with route of inhalation, and also suggest nasal removal is less than complete at high ventilation rates. There remains, however, some question whether studies using mouthpiece or nose clips overstate oral penetration of SO_2 under free breathing conditions and comparable oral ventilation rates (Cole et al., 1982). Direct measurements of SO_2 penetration under these conditions are not available in animals or humans. These matters are of some interest in quantitative evaluations of the numerous controlled human SO_2 experiments that involve mouth only exposures and the use of nose clips.

Except in the case of blockage of the nasal passages by mucus or other obstruction, typical "mouth breathing" is better characterized as oronasal breathing, since the larger portion of the inspired air does pass through the nose. Under test conditions, about 15% of subjects studied to date appear to be habitual oronasal or mouth only breathers (Saibene et al., 1978; Niinimaa et al., 1981). Anyone may shift to oronasal breathing during conversation, singing, illness with nasal congestion, or exercise. High levels of SO_2 may increase nasal airflow resistance to the extent that the oral portion of breathing is increased (Andersen et al., 1974). Most individuals shift to oronasal breathing at flow rates greater than 30-35 l/min (Niinimaa et al., 1981), which is roughly equivalent to moderate exercise as in walking briskly or bicycling (Cotes, 1979). At this ventilation rate, about 43% of the inspired air bypasses the nose (Niinimaa et al., 1981). Table A-1 summarizes ventilation patterns observed in "mouth" breathers and normal subjects.

Exercise or its analogue, deep breathing, can increase penetration of SO_2 both through increased ventilation and by causing a shift to oronasal breathing. Increasing nasal flow rate from 3.5 l/min to 35 l/min increased tracheal penetration of SO_2 in dogs from 0.01% to about 3.2% (Frank et al., 1969). In the same experiments, the combination of changing from nose to mouth only breathing and increasing ventilation rate from 3.5 to 35 l/min increased tracheal penetration of SO_2 from 0.01% to about 70%. Theoretical (Aharonson, 1976) and empirical (Brain, 1970) evidence indicates that besides increasing penetration of SO_2, higher ventilation rates result in increased deposition of SO_2 into the mucosal lining of the upper airways. A number of human studies generally support the notion that increased ventilation results in increased penetration and deposition as indicated by enhanced functional responses and/or increased symptoms (Kreisman et al., 1976; Lawther et al., 1975; Sheppard et al., 1981a; Stacy et al., 1981). Of particular interest in this regard is the similarity in both the time course and magnitude of SO_2-induced bronchoconstriction observed under modified hyperventilation and under exercise (Sheppard et al., 1981a).

TABLE A-1. ORONASAL DISTRIBUTION OF INSPIRED AIR[1]

Ventilation Rate (l/min)	Normal Breathers		"Mouth-Only" Breathers		Representative Activity[2]
	Nasal Volume (l/min)	Mouth Volume (l/min)	Nasal Volume (l/min)	Mouth Volume (l/min)	
5	5	0	4	1	Sleep
10	10	0	6	4	Standing
15	15	0	8	7	Walking normally (2 mph)
20	20	0	9	11	Walking slow (1 mph), carrying 10 lb. load
30	30	0	12	18	Walking quickly (4 mph)
35.3*	19.8	15.5	13	22	Climbing 3 flights of stairs, light cycling and snow shoveling
40	21	19	14	26	Light jogging, tennis (singles)
45	22.5	22.5	15	30	Climbing 4 flights of stairs, moderate cycling, chopping wood
50	23	27	17	33	Light uphill running (8.6% grade), gymnastics
60	28	32	18	42	Moderate jogging (7 mph)
80	32	48	23	57	Heavy cycling, climbing 7 flights of stairs
90	36.5	53.5	-	-	Heavy exercise, e.g., basketball, running (11 mph)

[1] From Niinimaa et al. (1981)

[2] From NAS (1958); Morehouse and Miller (1948); Karpovich (1953); Rossier et al. (1960); Zenz (1975); and Cotes (1979). Activities are derived from average maximal oxygen consumption and a range of ventilatory rates at each activity for healthy men. Because there is great variation in breathing requirements among people, these can only be considered as approximations.

*Point at which normal breathers switch from nasal only breathing to oronasal breathing.

Most studies investigating the effects of exercise or hyperventilation used mouth only exposure to SO_2; the penetration of SO_2 and resultant effects for exercise related oronasal breathing are, as expected, somewhat lower than that reported for mouth only breathing, at comparable total ventilation rates (Kirkpatrick et al., 1982; Linn et al., 1982a).

B. Absorption by Particles

An additional factor hypothesized to increase penetration of SO_2 is absorption onto particles capable of penetrating to the thoracic regions (CD, p. 11-37 to 11-38). Direct measurements of the extent to which penetration might increase are not available. Theoretical considerations summarized in Section IV-A suggest that at realistic peak levels of particle/SO_2 combinations ($\leq$ 1000 $\mu g/m^3$), only a relatively small amount of SO_2 can be attached to or dissolved in particles. Nevertheless, both animal and human studies have sometimes reported apparent "synergistic" increases in responses to exposures to SO_2 and certain aerosols (CD, Tables 12-11 and 13-14). In some cases, the increased response is attributed to the formation of sulfuric acid by catalytic metals (Amdur and Underhill, 1968), but the combinations of SO_2 and water droplets or NaCl aerosols used in most animal and human studies are unlikely to produce an enhanced response through an oxidation mechanism (McJilton et al., 1976). In this case, droplet aerosols containing H^+, HSO_3^-, SO_2, NH_3, and dissolved electrolyte penetrate the thoracic region and result in discrete "hot spot" deposition characteristic of particles as well as the more diffuse gas deposition from SO_2 released from the droplet in deeper regions.

The mixed results observed with regard to potentiation of SO_2 effects by non-catalytic dry particles and droplet aerosols appear consistent with the extent to which those particles can increase SO_2 penetration. SO_2 absorption by dry aerosols is limited by particle surface area and the amount absorbed is likely to be a small fraction of particle mass, particularly for coarse particles. High concentrations (60 mg/m^3) of coarse (6 to 8 µm) NaCl aerosols did not increase response to 5 ppm SO_2 in humans (Snell and Luchsinger, 1969). In animal experiments, 10 mg/m^3 of dry submicrometer NaCl potentiated response to 2 ppm SO_2, but 4 mg/m^3 of the same aerosol was insufficient to enhance effects (Amdur, 1961). In human studies, high levels of submicrometer NaCl ($>$ 7 mg/m^3) have either enhanced (Toyama, 1964) or failed to enhance (Frank et al., 1964) SO_2 effects. Humidity was not reported in these studies.

An equivalent mass of neutral pH droplet aerosols can absorb more SO_2 than can dry particles and thus increase response. This was apparently shown in animal exposures to dry and droplet NaCl aerosols by McJilton et al. (1976), and suggested in human studies by the distilled water-SO_2 combinations used by Snell and Luchsinger (1969). Conditions that favor increased SO_2 penetration through dissolution in droplets include: 1) Higher droplet pH resulting from increased ammonia levels in chambers (as in animal studies) or in ambient air can dramatically increase dissolved SO_2. Higher ammonia concentrations in the mouth (Larson et al., 1982) may thus actually increase effective penetration of SO_2 levels by increasing SO_2 solubility (CD, p. 2-67). Conversely, sulfuric acid droplets absorb little SO_2; 2) High humidity - this favors formation of hygroscopic aerosols or fog droplets; 3) Low temperature - SO_2 is more soluble at colder temperatures; and 4) High droplet aerosol concentration.

C. Mechanisms of Toxicity

The major mechanisms of potential interest in SO_2 toxicity can be categorized as outlined below:

1. Irritation of tissues or nerve receptors leading to airway functional changes

Rapid bronchoconstriction (airway narrowing) is the major response to short-term (< 1-hour) exposures to SO_2 at realistic peak ambient levels (CD, p. 1-57). In both human and animal studies, it appears that this response results from stimulation of irritant or "cough" receptors located in the larynx, trachea, and more central bronchii and a reflex contraction of bronchial smooth muscles, as mediated by neural pathways involving the vagus nerve (Widdicombe, 1954; Nadel et al., 1965; Sheppard et al., 1981a). The relative importance of the potentially responsible agent(s) ($H_2O{\cdot}SO_2$, sulfite, bisulfite, or hydrogen ion) is not known with certainty. The mechanism(s) of action may include reaction of dissolved SO_2 or one of the products of hydration with nerve endings (NAS, 1978, p. 7-10), or irritation of surrounding tissues leading to release of agents that act on nearby receptors or are transported by the blood (CD, p. 12-14).

The mechanism by which airway constriction occurs for a particular species may be influenced by the underlying state of health, time course of exposure, and concentration, which may be more important than duration of exposure (CD, p. 12-76). Direct action by SO_2 or locally released agents is most likely involved in the reflex bronchoconstriction that develops within minutes and tends to subside after 10 to 15 minutes or at the end of exposure (Corn et al., 1972; Frank and Speizer, 1965; Frank et al., 1964, Melville, 1970). Recent evidence suggests that SO_2

might trigger reflex bronchospasm in asthmatics by stimulating the release of mediators (e.g., histamine) from mast cells (Sheppard et al., 1981b). Induced release of humoral agents with delayed action or increased secretion or pooling of mucus might be responsible for the progressive airway narrowing associated with continued exposure in guinea pigs over a period of hours (Amdur, 1959) and, after intermediate time periods (hours - days), in humans (Andersen et al., 1974; Weir and Bromberg, 1972). In contrast to rapid recovery of normal humans to short-term peaks noted above, responses in guinea pigs may require an hour or more to return to normal values (Amdur, 1959).

Although evidence is not conclusive, peak or prolonged SO_2 exposure may also increase sensitivity of bronchial receptors to subsequent irritation by other bronchoconstrictive agents, as suggested by small to moderate increases in reactivity to acetylcholine in dogs (Islam et al., 1972) and humans (Reichel, 1972) following SO_2 exposures. At high concentrations (17 ppm), SO_2 produces a transient depression in respiratory rates in mice, possibly mediated through a neural reflex following stimulation of receptors in the nasal region (Alarie, 1973). Available data do not suggest this is an important mechanism in human responses to peak ambient levels.

Because the smooth muscles involved in reflex bronchoconstriction fatigue or become adjusted to altered tone over time and because long-term penetration of SO_2 to the tracheobronchial region is limited by upper airway removal, chronic exposure to SO_2 alone is not likely to cause permanent changes in bronchial tone (CD, p. 12-19). Indeed, long-term exposures, alone (< 5 ppm SO_2) and in combination with dry fly ash or sulfuric acid in animals have not produced notable changes in respiratory function (Alarie et al., 1970, 1972, 1973, 1975). Repeated peak exposures have not been adequately tested.

2. Alteration of clearance and other host defense systems

This may result in increased susceptibility to infection or contribute to chronic respiratory disease. The effect of SO_2 on clearance apparently varies with region of the respiratory tract, species, and nature of exposure. SO_2 may affect clearance rates by affecting physicochemical properties of the mucus, increasing mucous secretion, damage to cilia, or altering deposition patterns through bronchoconstriction. SO_2 (5 ppm) decreased nasal mucous flow rates in 3- to 6-hour human exposures (Andersen et al., 1974). The implications of this response for susceptibility to infection are, however, unclear (Andersen et al., 1977). Short-term oral exposure to 5 ppm SO_2 during exercise enhances exercise induced increases in tracheobronchial clearance in healthy adults (Wolff et al., 1975a; Newhouse et al., 1978), but no effects are seen at rest (Wolff et al., 1975b). Effects of repeated peak and long-term exposures in animals suggest a biphasic response; slightly accelerated clearance and no change after several days followed by increasingly decreased clearance with time or higher SO_2 levels (Spiegelman et al., 1968; Farin and Leach, 1973; Hirsch et al., 1975). Similar biphasic responses have been noted for sulfuric acid (at lower concentration than SO_2) and cigarette smoke (Leikauf et al., 1981). Because SO_2 effects on clearance may also be mediated through a reflex response (Wolff et al., 1975a), clearance may be affected in airways distal to the site of SO_2 deposition.

Because little SO_2 penetrates to the pulmonary region, substantial direct effects on pulmonary macrophages are not expected; none have been observed (Katz and Laskin, 1976). From limited infectivity work in animals, it appears that susceptibility to bacterial infection is not affected by high SO_2 concentrations (5 ppm for up to 3 months) (Ehrlich et al., 1978). Antiviral defenses were impaired by SO_2 in mice, but only at high levels (7 to 10 ppm) for 7 days (Fairchild et al., 1972; Lebowitz and Fairchild, 1973). Long-term exposure to 2 ppm alone and in combination with 560 $\mu g/m^3$ of carbon dust for 192 days altered pulmonary and systemic immune systems (Zarkower, 1972). Effects of the combined exposure were at most additive and dominated by carbon.

3. Tissue irritation or damage leading to morphological alterations

Because most SO_2 is deposited in the upper airways, the potential for damage is greatest in the upper respiratory passages (Giddens and Fairchild, 1972; Hirsch et al., 1975). High concentrations (repeated peaks of 50 ppm) produced damage to the mucous secreting cells in the bronchial airways of rats (Reid, 1970). At lower long-term exposures (0.14 to 5.1 ppm), SO_2 alone and in combination with dry fly ash particles produced no significant morphological alterations in bronchial airways or alveolar regions of monkeys (Alarie et al., 1972).

4. Reactions with important cellular constituents

The three major reactions of bisulfite (e.g., from dissolved SO_2) with biological materials include sulfonation, auto-oxidation, and addition to cytosine (CD, p. 1-57). A number of *in vitro* studies have suggested that these reactions may result in effects on enzyme systems, but, because major *in vivo* studies of these endpoints have not been conducted, no evidence exists indicating effects in whole animals or humans (CD, p. 12-7). Production of free radicals during auto-oxidation (CD, p. 12-4) and the reaction with cytosine in DNA are mechanisms by which bisulfite might induce mutation (Shapiro, 1977). SO_2 and bisulfite are mutagenic in microbial systems at acid pH, but cytotoxicity, rather than mutagenicity, is the most common response of cultured animal or human cells (Thompson and Pace, 1962; Kikigawa and Iizuka, 1972). Animal studies using high concentrations provide some suggestion that SO_2 might be a carcinogen or co-carcinogen with benzo-a-pyrene. (Peacock and Spence, 1967; Laskin et al., 1970, 1976). The evidence is, however, inconclusive (CD, p. 12-78).

APPENDIX B. EVALUATION OF EVIDENCE FOR EFFECTS ON RESPIRATORY MECHANICS AND SYMPTOMS

This section discusses and evaluates the key studies providing information on the effects of SO_2, alone and in combination with other pollutants, on respiratory mechanics and symptoms.

A. Controlled Human Studies of SO_2 Alone

Although differences in aspects such as respiratory function indicators, subject activity levels, and routes of exposure make direct comparisons difficult, the major observed response to short-term exposures of SO_2 appears to be bronchoconstriction, usually evidenced in increased pulmonary flow resistance or impaired forced expiratory flow rates. The data indicate that most healthy adult subjects respond to short-term SO_2 exposures of 5 ppm or more (Table 5-1, Section V; CD, p. 13-48). At lower levels, (1-4 ppm) results are more mixed, with a number of studies reporting otherwise normal individual "hyperreactors." At 1 ppm, Frank et al. (1962) reported a significant increase in pulmonary flow resistance in one of 11 subjects during exposures lasting 15 minutes. Also at 1 ppm, Andersen et al. (1974) found a small but progressive decrease in forced expiratory flow ($FEF_{25-75\%}$) and forced expiratory volume ($FEV_{1.0}$) and an increase in nasal flow resistance in 15 adults exposed for 6 hours. With intermittent exercise, levels of 0.75 ppm SO_2 resulted in decreases in several functional parameters in apparently healthy adults (Bates and Hazucha, 1973; Stacy et al., 1981). The major responders in the Stacy work might have been defined as mild atopics. Other work indicates that such individuals are substantially more responsive to SO_2 than normal subjects (Koenig et al., 1982a,b; Sheppard et al., 1981a).

Asthmatic subjects appear to respond to SO_2 at levels an order of magnitude lower than do healthy adults. Several studies in Table 5-1

(Section V-B of main text) report marked changes in functional measurements after short-term ($\leq$ 1 hour) oral (mouthpiece) exposure at rest and during exercise at levels of 1-5 ppm with symptoms such as wheezing and shortness of breath increasing with concentration. A number of subjects were reportedly unable to tolerate these exposures. Symptomatic responses are reported at levels as low as 0.5 ppm for 10 minutes (Sheppard et al., 1981a; Kirkpatrick et al., 1982). Decreased functional measurements can occur for oral (mouthpiece) exposures of 0.25 to 0.5 ppm with exercise (Sheppard et al., 1981a). In this study, the two most sensitive asthmatic subjects exibited increased airway resistance (without symptoms) for mouthpiece breathing and exercise at levels of 0.1 ppm.

A number of studies suggest that acute reflex respiratory mechanical changes induced by SO_2 take place within a relatively short period of time, on the order of 1 to 5 minutes (e.g., Frank et al., 1964; Melville, 1970; Lawther et al., 1975). Deep breathing accompanying exercise can temporarily reverse this bronchoconstriction (Nadel and Tierny, 1961) and can delay the onset of respiratory changes (Sheppard et al., 1981a) and otherwise lengthen the period in which decrements occur (Bates and Hazucha, 1973). Responses are usually maximal within 10 minutes, and may decrease somewhat and/or remain about constant for exposures of up to one hour (Melville, 1970). This is in contrast to the steady increase in resistance reported for guinea pigs over similar periods (Amdur, 1959).

After short-term exposures, recovery to normal functional values can occur rapidly, in as little as 5 minutes in normal resting subjects (Lawther et al., 1975), but may take 30-60 minutes for exposures involving exercise (Bates and Hazucha, 1973), asthmatic subjects with exercise

(Sheppard et al., 1981a; Koenig et al., 1981), or other sensitive subjects (Lawther et al., 1975; Gökemeijer et al., 1973). In one study, (Jaeger et al., 1979) symptomatic responses (wheezing and shortness of breath) observed in three sensitive subjects (out of 80) did not occur until the evening following a quiescent oral (nose clips) 3-hour exposure to 0.5 ppm SO_2. In this study, only very small decreases in one functional response were seen immediately following exposure in most subjects and it is not clear how SO_2, acting alone, could have produced such a delayed response. Nevertheless, of the three reactors, two were asthmatics who had been free of wheezing for several months before the experiment and one (non-diagnosed) had never experienced wheezing previously, suggesting some involvement of the exposures. One plausible explanation is suggested by the observations of Islam et al. (1972) and Reichel (1972), outlined in Section V-A, namely that SO_2 may sensitize airways to subsequent bronchoconstrictive challenge. Thus, in this case, the attacks might have been proximally caused by post-experimental exposures to other substances. Additional work is needed to determine the extent to which such SO_2 levels may increase airway sensitivity.

Three controlled studies of longer SO_2 exposures (> 3 hrs to days) suggest the possibility of somewhat different respiratory responses. Andersen et al. (1974) found that chamber (mostly at rest, nasal breathing) exposure to 1 ppm SO_2 produced a progressive decrease in forced expiratory flow ($FEF_{25-75\%}$) and to a lesser (nonsignificant) extent $FEV_{1.0}$ over a six hour period. Changes were slight after 1 to 3 hours and were small but significantly larger for one parameter ($FEF_{25-75\%}$), after 6 hours. There was some suggestion of a carry over of functional decrement after exposure into the next day (≈ 18 hours), although the carry over was more convincing after a similar 5 ppm, 6 hour exposure. Some slight discomfort and symptoms were noted at this higher concentration.

Weir and Bromberg (1972) exposed 12 healthy subjects and a selected group of seven otherwise healthy smokers with evidence of early small airway functional impairment for 5 and 4 days respectively to 0.3, 1, and 3 ppm of SO_2. Subjects were free breathing and may have exercised, but such occurrences were not reported. No effects were noted at the 0.3 ppm level in either group. In the healthy group, small but significant decreases in compliance were noted at 1 and 3 ppm. These changes were maximal at the first measurement (24 hours), decreased to insignificant levels over the next several days, and finally increased again after 120 hours in the 3 ppm exposure group. Recovery to normal values was complete 48 hours after exposure. The authors suggest that the early changes were the result of the reflex bronchoconstriction observed in short-term studies, an effect which can diminish with continued exposure. The later effects, they argue, may represent a different mechanism of damage. Responses in the impaired group were reported to be so variable under both controlled and exposure conditions that consistent responses (mechanics or symptoms) to SO_2 were not detectable. Under the conditions of study (steady multiday exposures, mostly resting) the impaired group was not more sensitive to the effects of SO_2.

Reichel (1972) reported a gradual, but not statistically significant increase in intrathoracic gas volume in normal subjects exposed for 6 days to 7.7 ppm SO_2. No trends in airway resistance were noted. All subjects complained of various symptoms such as rhinitis, conjunctivitis and throat irritation. In this study, the frequency of increased obstructive bronchial reactions to acetylcholine increased as a result of the exposure.

Bronchitic patients were also exposed but to lower levels (1.5 to 3.8 ppm SO_2, 4 or 6 days). One of the groups with more serious obstructive disease appeared to show a decrease in total resistance but no statistics are given and the discussion suggests that no responses were seen. The results on bronchitics are confounded because the patients had to be treated by medicative therapy during the exposure; thus conclusions about their relative sensitivity at these exposures are not possible.

In these long-term studies, SO_2 exposures were increased gradually from control to maximum levels over a period of hours. This apparently reduces the chance of more severe bronchoconstriction observed in short-term studies after abrupt increases in concentration over a period of seconds. Andersen et al. (1974), for example, observed that subjects slowly brought to 5 ppm reported only mild discomfort while the investigators entering the 5 ppm chamber from clean air felt "strong discomfort and a cough which was difficult to suppress but disappeared after a few minutes." The time course of flow reduction during free breathing chamber exposures to 0.75 ppm SO_2 observed by Bates and Hazucha (1973) and Stacy et al. (1981) suggest that the rapid rise in ventilation brought on by the onset of intermittent exercise may be equivalent to a sharp increase in concentration. In the Bates study, $MEFR_{50\%}$ continued to decrease throughout a 2-hour exposure with periodic exercise. In the Stacy study, subjects were exposed at rest for 45 minutes to 0.75 ppm SO_2 before beginning exercise. Based on previous work on resting healthy adults, it is highly unlikely that constrictive effects would have been observed during the resting exposure. Despite this extended exposure prior to exercise, airway resistance still increased significantly following a 15-minute exercise period. This is consistent with expectations in that even though external SO_2 levels remained constant, the effective concentration at sensitive receptors increased rapidly with the increased oronasal ventilation associated with exercise.

B. Long-term Exposures to SO_2 Alone

As discussed in Section V-A, long-term exposures of laboratory animals to moderate SO_2 levels have not generally been observed to produce decrements in respiratory mechanics (CD, Table 12-3). The only exception is the work of Lewis et al. (1969, 1973), who found increased pulmonary flow resistance and decreased lung compliance in dogs exposed to 5.1 ppm SO_2, 21 hours a day for 225 days. After 620 days, nitrogen washout increased, but the other functional parameters were no longer significantly different. This high level exposure of apparently resting animals used in this and most animal studies may not adequately assess the potential long-term effects associated with repeated peak exposure and intermittent exercise characteristic of human exposures.

C. SO_2 in Combination with Laboratory Particles, Other Gases

The interaction of SO_2 with particles and with pollutant gases has been variously reported to produce responses on respiratory mechanics and symptoms sometimes exceeding those attributable to the two agents administered separately, and sometimes not. Enhanced responses may arise from physical sorption of SO_2 on or in particles permitting enhanced respiratory penetration of the gas (Appendix A), chemical reactions to form irritant pollutants (e.g., stable sulfites or sulfuric acid), and deposition and combined actions of SO_2 and particles or pollutant gases in various sites in the respiratory tract.

Amdur and coworkers studied combinations of SO_2 and particles in the guinea pig model already shown to be quite sensitive to both SO_2 and sulfates. The results of fine aerosol/SO_2 mixtures at low humidity, typically administered for an hour, can be summarized as follows: 1) soluble catalytic aerosols (containing manganese, ferrous iron, or vanadium) potentiated the response to SO_2 by reactions in the chamber or in the animal that apparently formed a more irritant aerosol (e.g., sulfuric acid or sulfite complex); 2) certain salt aerosols (NaCl, KCl, NH_4SCN) potentiated SO_2 response in order of increasing SO_2 solubility, but only at unrealistic levels (10 mg/m^3) (Amdur and Underhill, 1968); 3) combinations of SO_2 and the most common atmospheric sulfate species (ammonium sulfates, sulfuric acid) produced additive responses (Amdur et al., 1978a), and; 4) SO_2 and insoluble dry aerosols (carbon, activated charcoal, fly ash, ferric oxide, manganese dioxide, and motor oil) produced, at most, additive responses (Amdur and Underhill, 1968; Costa and Amdur, 1979).

As noted, the Amdur studies were apparently conducted at low relative humidity (< 70%). Work on guinea pigs by McJilton et al. (1976) found no response to a one hour exposure to SO_2 (1 ppm) and sodium chloride (1 mg/m^3) aerosol at low relative humidity (RH), but a marked potentiation at high RH (80%) that allowed droplet formation. Droplet pH prior to exposure was 3.8 with no detectable sulfate formation. Chamber ammonia, which might have increased SO_2 solubility in the droplets, was not measured.

A few controlled human studies have examined combinations of SO_2 and particulate matter, chiefly sodium chloride, water droplet aerosols, and carbon particles. Dry salt/SO_2 combinations support the McJilton et al. (1973) results in animals, that is, moderate levels ($\leq$ 1000 $\mu g/m^3$) of dry salt particles do not potentiate the effect of SO_2 (Frank et al., 1964; Burton et al., 1969; Snell and Luchsinger, 1969). Some Japanese work suggest a possible potentiation by dry salt (Toyama, 1962; Nakamura, 1964), but these studies used high salt (7 mg/m^3) or SO_2 (9 ppm) levels, and, according to the criteria document (p. 13-27) and NAS (1978) used inadequate functional measurements. In contrast to McJilton and Frank, however, Koenig et al. (1982a,b) found no evidence of potentiation in humans using virtually the same SO_2/NaCl droplet aerosol. Possibly, this disparity is due to the presence of ammonia in the animal chamber, but not in the human exposure.

The results of Snell and Luchsinger (1969), provide some controlled human evidence that water droplet aerosols may potentiate the effect of SO_2 by increased penetration and/or hot spot deposition. Increased effects were suggested for SO_2/water droplet aerosol combinations, but the resultant decrease in pulmonary function was independent of SO_2 concentration; thus enhancement occurred only at lower SO_2 levels ($\leq$ 1 ppm). Unfortunately, water droplet levels could not be estimated, ammonia levels are not known, and the functional measurement techniques used are of questionable validity (CD, p. 13-51; Kreisman et al., 1976).

Andersen et al. (1981) examined nasal exposure to combinations of SO_2 (1 or 5 ppm) and a coarse (2-15 μm) plastic dust (2 or 10 mg/m^3) with and without a surface coating of vanadium oxide. Effects on nasal mucous flows, nasal air flow resistance, forced expiratory flow ($FEF_{25-75\%}$) and symptomatic discomfort were, at most, additive. This is not suprising since most of the coarse aerosol did not penetrate the nose and adsorption of SO_2 on dry insoluble aerosols (e.g., carbon) is probably minimal (Schryrer et al., 1980).

In summary, although particles may potentiate the effect of SO_2 by increased penetration or chemical reaction, controlled human exposures have found mixed results, with little convincing evidence that such enhancement occurs for laboratory aerosol conditions at realistic peak aerosol levels. Ambient conditions that might tend to maximize interactions between SO_2 and particles (cold temperatures, fog droplets, substantial NO_2, NH_3) have not been systematically examined in the laboratory.

Long-term exposures to SO_2 in combination with particulate pollutants have been conducted only in animals, and are evaluated in Appendix B (Table B-8) of the particulate matter staff paper (EPA, 1982b). These studies in general have either found no lasting mechanical responses or the functional decrements appear less important than underlying damage; deep lung damage in such cases (Gillespie et al., 1980) does not appear related to the SO_2 component of the mixtures (EPA, 1982b).

Combinations of SO_2 and other atmospheric gases have produced mixed results. Bates and Hazucha (1973) first reported synergistic functional responses to $SO_2 + O_3$ (0.37 ppm each), but follow up studies in other laboratories and with other investigators (Bell et al., 1977; Horvath and Folinsbee, 1977; Bedi et al., 1979) did not confirm these results. Follow-up measurements by Bell et al. (1977) suggested that the system used in the original study may have produced ultrafine sulfuric acid and other sulfate aerosol formation (total sulfates as high as 200 $\mu g/m^3$) and may have permitted intrusion of ambient particles. The result of a follow up study by Kleinman et al. (1981) with 0.4 ppm SO_2, O_3 and 100 $\mu g/m^3$ sulfuric acid/ammonium sulfate aerosol found, however, only a small incremental response over ozone alone; the increment was much smaller than observed by Hazucha and Bates. A recent Japanese study

(Kagawa and Tsuru, 1979) reports that exposures to $SO_2 + O_3$, (0.15 ppm each) results in a greater than additive increase in airway resistance, but not to the extent seen by Hazucha and Bates. The finding of small significant responses in this study may be related to differences in methods of statistical analyses (Bedi et al., 1982). In summary, the available evidence on synergism between O_3 and SO_2 or O_3, SO_2, and sulfates suggests reason for caution, but the question is unresolved. Combinations of SO_2 with NO_2 and O_3 at both high and low levels (CD, Table 13-5) resulted in no enhancement of functional changes (Linn et al., 1980; von Nieding et al., 1979).

D. Community Air Pollution

Qualitative examination of short-term respiratory mechanical changes in people exposed to fluctuating ambient levels of SO_2 and particles are limited to two epidemiological investigations. Lawther et al. (1974a,b,c) made daily measurements of lung function on four normal subjects for five years, and two bronchitics for one winter in London. Daily variations in lung function were small and mostly affected by respiratory infections, although some direct effects of pollution were detected. After multiple regression analysis, SO_2 concentrations explained the largest proportion of variance in peak flow rates (PEFR) and airway resistance (indicated by MMFR), with clearest associations shown after walking exercise during episodic periods of heavy pollution. These results are limited because of the small study group.

Small, but persistent declines in children's lung function ($FEV_{1.0}$) were observed after a pollution episode in Steubenville, Ohio in which SO_2 reached high 24-hour levels along with a somewhat lower TSP level (Dockery et al., 1981). Similar effects were noted following an episode dominated by high TSP levels and moderately high SO_2. The authors conclude that this study provides suggestive but inconclusive evidence regarding short-term (24-hour) changes in air pollution and $FEV_{1.0}$. The long-term significance of these changes has not been assessed.

A number of long-term epidemiological studies of chronic effects have found that populations living in areas characterized by high particulate matter and SO_2 tend to have a higher prevalence of respiratory illnesses and symptoms and lower lung function capability compared with other groups living in areas with lower pollution levels (see Table B-3, EPA, 1982b). Other qualitative studies discussed below have detected differences that might possibly be explained by contrasting exposures to SO_2 rather than other pollutants. As in most epidemiological studies, however, the influence of particles and other factors confound interpretation.

Neri et al. (1975) compared adolescents and adults in a large city with a similar group living near a large smelting operation (Sudbury, Ontario) that required frequent shutdowns because 24-hour pollution levels in town often reached "maximum permissible values" ($\geq$ 790 μg/m^3 [0.3 ppm] SO_2 or $\geq$ 400 μg/m^3 suspended particulate matter). After controlling for smoking and occupational differences, residents of the smelter town had significantly lower lung function than the city dwellers. The criteria document concludes that very high periodic peak ($\leq$ 1 hr) SO_2 exposure levels likely accounted more for any pollutant effects than long-term exposures to relatively low annual average levels of SO_2 or annual mean particulate levels (which did not vary by much between the two areas) (CD, p. 14-100).

The possibility that the lung function decrements as noted by Neri et al. may reflect the cumulative effects of repeated peak exposures has been examined in other Canadian cross-sectional studies. Comparisons were made between children (Becklake et al., 1978) and adults (Aubrey et al., 1979) living near point sources and exposed to high SO_2 peaks with similar groups in communities with little SO_2 pollution. Annual particle levels (TSP) were moderately high in all areas, with one of the peak SO_2 areas having frequent peaks of TSP as well. No significant differences in respiratory symptom prevalence were noted for either group nor in pulmonary function among the adults. However, among the children in the high pollution areas, small airway function (as measured by closing volume) was impaired, and a trend towards reduced lung function as the winter progressed was noted. The authors felt that these subtle effects might reflect the early stages of airway disease in the children exposed to high SO_2 peaks with or without accompanying high particulate matter peaks. Because of the preliminary nature of the study, the results can only suggest minor effects that might be weakly associated with repeated exposures to SO_2.

Van der Lende et al. (1973, 1975, 1981) followed a group of Dutch adults living in an industrialized town along with a similar group of rural residents for nine years. The initial cross-sectional comparison revealed no difference in lung function, although the prevalence of chronic cough and phlegm, and sputum production, was higher among the urban residents. Repeated follow-up studies were done at three year intervals over a period when the urban SO_2 levels decreased considerably from high (with frequent peaks) to more moderate levels, and particles (British Smoke) remained at relatively low levels. After controls for smoking and occupational differences, the urban residents showed an accelerated decline in lung function over that observed for rural residents. Difficulties in assessing exposure to particles (calibration of smoke data) and SO_2 (representativeness of monitor) limit interpretations of these results.

APPENDIX C. PULMONARY FUNCTION TESTS USED IN CONTROLLED HUMAN STUDIES OF SO_2[1]

A. Introduction

Pulmonary function tests can provide objective information to assist clinical judgment and help in the evaluation of respiratory impairment caused by air pollutants such as SO_2. The tests and terms used to describe various aspects of respiratory function referred to in this paper are defined in the glossary that follows this section.

These tests principally measure respiratory mechanics, which includes the combined effects of gravity, elastic recoil, and smooth muscle tone upon airway caliber, lung volumes and airflow patterns. Several tests have been developed in an attempt to differentiate among 1) kinds of effects; for instance airway narrowing or obstruction as in asthma, bronchitis, and emphysema, and restriction of the thorax, as in fibrosis or skeletal and chest muscle disorders, and 2) region or site of action; for instance the large airways (bronchi), small airways (bronchioles), and gas exchange regions.

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[1] General references for this Appendix include: Cotes (1979), Fishman (1976), Macklem and Mead (1967), Mead et al. (1967), and Wanner (1980).

B. Glossary of Terms used to Describe Respiratory Mechanics and its Tests

Airway conductance (G_{aw}): The reciprocal of airway resistance.

Airway resistance (R_{aw}, pulmonary flow resistance): Resistance to the flow of gas in the airways (one component of the total respiratory resistance) measured by body plethysmography. Average values for normal healthy individuals range from 0.6-2.4 cm H_2O/l/sec. A normal resting subject in whom bronchial obstruction is induced does not usually experience symptoms until R_{aw} is increased 3-fold or more and severe dyspnea may not result until R_{aw} is increased 5- to 15-fold. R_{aw} and its derivatives (G_{aw}, SG_{aw}, SR_{aw}) are mainly affected by alterations in the resistance characteristics of the large airways.

Alveolar oxygen tension (PA_{O2}): Partial pressure of oxygen in the alveolar airspace (reflects amount of oxygen in alveolar air).

Arterial oxygen tension (PA_{O2}): Partial pressure of oxygen in arterial blood (reflects amount of oxygen in arterial blood).

Bronchoconstriction: Constriction of the airways, may be caused by neural reflexes or direct effect on smooth muscle.

Bronchospasm: See bronchoconstriction.

Closing capacity (CC): The volume at which, during expiration, the closure and trapping of gas in the alveolus (caused by increase in applied pressure and reduction in the diameter of the small airways) first occurs; CC = RV + CV. The assumption is that with narrowing of the small airways, closure will occur at a higher lung volume.

Closing volume (CV): Volume of the lungs above residual volume where the closure and trapping of gas in the alveolus occur (detected by the change in expired nitrogen gas concentration); CV = CC - RV. CV is higher with narrowed small airways, as in smokers.

CC: See closing capacity.

CV: See closing volume.

Flow rate from 25-75% expired vital capacity ($FEF_{25\text{-}75\%}$): Flow rate measured from 25% to 75% of expired vital capacity.

Flow rate at 50% forced vital capacity ($FEF_{50\%}$): Flow rate measured with 50% expired vital capacity remaining. Same as MEFR. Primarily measures intermediate to large airway function.

Forced expiratory volume (FEV): Same as vital capacity.

Forced expiratory volume at 1.0 sec ($FEV_{1.0}$): Fraction of vital capacity expired in 1.0 second. Reduced in subjects with obstructive respiratory disease but not in those who have restricted expansion without obstruction. Mainly affected by alterations in the large airways.

Forced vital capacity (FVC): Same as vital capacity.

Functional residual capacity (FRC): The volume of air remaining in the lungs at the end-expiratory position. Measures small airway function.

$FEV_{1.0}$: See forced expiratory volume at 1.0 sec.

$FEF_{25-75\%}$: See flow rate 25-75% expired vital capacity.

$FEF_{50\%}$: See flow rate at 50% forced vital capacity.

FR: See respiratory frequency.

FRC: See functional residual capacity.

FVC: See vital capacity.

Maximum expiratory flow from 40% forced vital capacity ($MEF_{40\%}$): Maximum rate of flow during forced expiration at 40% vital capacity.

Maximum expiratory flow from 50% forced vital capacity ($MEF_{50\%}$): Maximum rate of flow during forced expiration at 50% vital capacity. Same as $FEF_{50\%}$. Primarily measures intermediate to large airway function.

Mid-maximal expiratory flow rate (MMFR, MMF, $MEF_{50\%}$): See maximum expiratory flow from 50% forced vital capacity. Same as $FEF_{50\%}$.

MEF 40%: See maximum expiratory flow from 40% forced vital capacity.

MEF 50%: See maximum expiratory flow from 50% forced vital capacity.

MEFR 50%: See maximum expiratory flow from 50% forced vital capacity.

MMFR: See mid-maximal expiratory flow rate.

Nitrogen washout test: Method to assess the uniformity of distribution of ventilation throughout the lungs; measures residual volume, functional residual capacity, and closing volume.

PA_{O2}: See alveolar oxygen tension.

Pa_{O2}: See arterial oxygen tension.

Residual volume (RV): Volume of a gas that remains in the lung at the end of a complete expiration.

R_{aw}: See airway resistance.

RV: See residual volume.

R_T: See total respiratory resistance.

Specific airway conductance (SG_{aw}): Extent to which the airways conduct the flow of gas normalized to the individual's thoracic gas volume:

$$SG_{aw} = \frac{G_{aw}}{TGV}$$

Specific airway resistance (SR_{aw}): Resistance to flow in the air ways normalized to the individual's thoracic gas volume; $SR_{aw} = R_{aw} \times TGV$.

SR_{aw}: See specific airway resistance

SG_{aw}: See specific airway conductance.

Thoracic gas volume (TGV): Volume of gas in the thorax, whether in free communication with the airways or not.

Total respiratory resistance (R_T): Total resistance of the respiratory system consists of three components, airway resistance, lung tissue resistance, and thoracic cage resistance. Primarily measures large airway function.

TGV: See thoracic gas volume.

Vital capacity (VC): Maximum volume of gas that can be expelled from the lungs by forceful effort following a maximal inspiration. Reduction of VC may be due to loss of distensible lung tissue or some type of limitation of respiratory movement not related to disease of lung tissue.

$V_{max50\%}$: Maximum flow calculated at 50% of expired vital capacity from a partial flow volume curve begun from approximately 60% of inspired vital capacity. Primarily reflects changes in the caliber of the small airways.

$V_{max75\%}$: Maximum flow calculated at 75% of expired vital capacity from a partial flow volume curve begun from approximately 60% of inspired vital capacity. Primarily reflects changes in the caliber of the small airways.

APPENDIX D. ANALYSIS OF ALTERNATIVE AVERAGING TIMES AND EXPOSURE

This appendix summarizes important aspects of several air quality, modeling, and exposure analyses (Frank and Thrall, 1982; Burton et al., 1982; Anderson, 1982) that were conducted in direct support of this staff paper. The information is used to support discussions of alternative averaging times and population exposure in Sections VI and VII. The major questions examined include: 1) the usefulness of a 24-hour standard as a surrogate for a 1-hour standard; 2) the relative protection afforded by current and alternative standards in the ranges of interest specified in Section VI; 3) the impact of eliminating the annual SO_2 standard; and 4) how many people are potentially exposed to 1-hour SO_2 values of 0.5 to 0.75 ppm, the range of interest used for the August 1982 draft of this staff paper. The reader is directed to the complete reports for a more detailed discussion of the issues addressed, methodology, and results. Further work, particularly in specifying population exposures and examining the lower bound of 1-hour SO_2 values recommended by CASAC (0.25 ppm) following their review of the August draft, is underway in support of decision-making on the review of the SO_2 standards.

A. Analysis of SO_2 Air Quality Data

Frank and Thrall (1982) examined SO_2 monitoring data collected during 1979 and 1980 representing 11 million hourly values at approximately 900 monitoring sites. Summary statistics for this data set are given in Tables 4-1 and 4-2 in Section IV. Sites were classified according to three types: population-oriented, source-oriented (excluding smelters), and smelter-oriented. Because of the limited and variable number of sites per area (typically 1 or 2 for source-oriented sites), differences in site location criteria and data completeness, and assumptions needed in scaling data, generalizations based on these analyses should be derived and used with caution.

1. 24-hour Standard as a Surrogate for 1-Hour Average

The relationship among various measures of 1-hour and 24-hour standards is examined in a series of tables and figures (Frank and Thrall, 1982). The usefulness of a 24-hour standard as a surrogate for a 1-hour standard depends on the extent to which the 24-hour standard limits 1-hour values to acceptable levels without causing additional controls in areas where both 24-hour and 1-hour air quality is already acceptable. Table D-1 shows that current control programs already limit the 2nd maximum 1-hour values in most site-years examined. The distribution of 1-hour values versus 24-hour values shows that tightening of the 24-hour standard to 0.12 ppm would not change the 1-hour status of over 60% of the sites with second maximum 1-hour values in excess of 0.5 ppm. Relaxing the 24-hour standard to over 0.16 ppm could permit a substantially larger number of sites with second maximum 1-hour values above 0.75 ppm.

Figure D-1 is a graphic display of the same data. The figure indicates that a 24-hour standard in the 0.12 to 0.14 range would control maximum 1-hour values at virtually all population-oriented sites. At many smelter and other source-oriented sites, the current 24-hour standard would be a useful surrogate only if current air quality were considered acceptable. As indicated in Figure D-1 and in Tables 7 and 8 of Frank and Thrall (1982), current air quality at many of these sites involves multiple hourly exceedances of 0.5 to 0.75 ppm SO_2. Reducing the 24-hour standard to 0.12 ppm would not result in improvements in most of the sites with high 1-hour values, but would call for additional controls at a number of sites meeting the current 24-hour standard with no second maximum 1-hour values higher than 0.5 ppm. Thus, TABLE D-1. CURRENT STATUS OF SECOND HIGH 1-HOUR VALUES VERSUS SECOND HIGHEST 24-HOUR VALUES IN TERMS OF SITE—YEARS (FRANK AND THRALL, 1982).

	2nd Highest 1-Hour Values (ppm)	Number of Site-Years	2nd Highest 24-Hour Values(ppm)			
			≤0.12	0.13-.14	0.15-.16	>0.16
All Sites*	≤ 0.25	938	938	0	0	0
	0.26-0.50	316	305	5	3	3
	0.51-0.75	73	54	11	4	4
	> 0.75	50	19	7	3	21
Population	≤ 0.25	634	634	0	0	0
	0.26-0.50	109	107	2	0	0
	0.51-0.75	10	6	2	0	2
	> 0.75	0	0	0	0	0
Source	≤ 0.25	264	264	0	0	0
	0.26-0.50	181	176	1	2	2
	0.51-0.75	48	39	4	3	2
	> 0.75	19	10	3	1	5
Smelter	≤ 0.25	5	5	0	0	0
	0.26-0.50	15	13	1	1	0
	0.51-0.75	14	9	5	0	0
	> 0.75	30	9	4	2	15

* "All Sites" category includes data which could not be classified as population, source, or smelter.

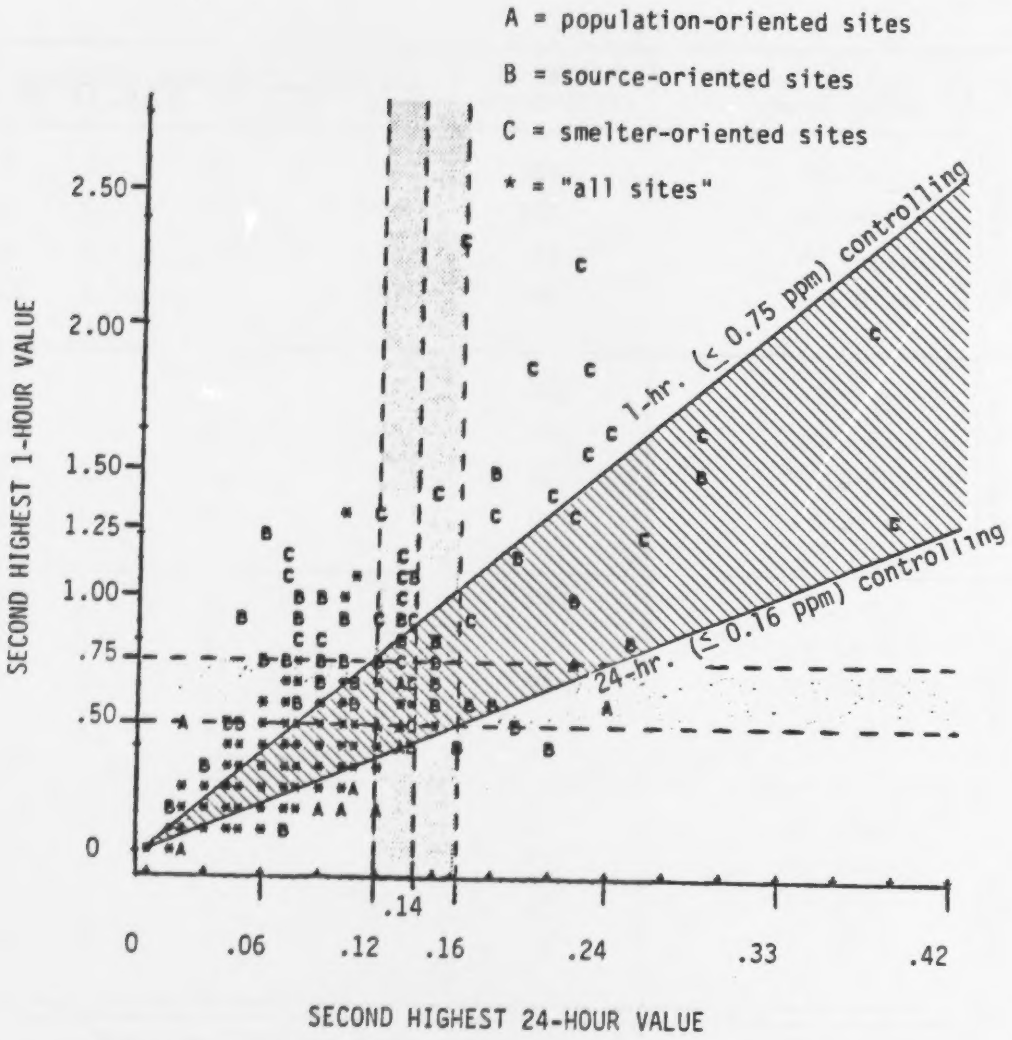

Figure D-1. Basic relationships between the second highest 1-hour value per year and the second highest 24-hour value (After Frank and Thrall, 1982). The initial staff ranges of interest for 1-hour standard (0.5 to 0.75 ppm) and possible 24-hour surrogates (0.12 to 0.16 ppm) are indicated by shading. Sites with data above the diagonal line(s) would be "controlled" by 1-hour standards, while those below the diagonals would be controlled by 24-hour standards. In the hatched area, the controlling standard would vary. Based on the data in this figure, the current 24-hour standard would keep 1-hour values below 0.5 ppm in almost all of the population oriented sites, but would not prevent many of the source and most of the smelter sites from having at least two 1-hour values per year in excess of the indicated range.

a 24-hour standard that would markedly improve maximum 1-hour air quality at most sites would be unnecessarily restrictive at sites with acceptable air quality.

2. Impact of Eliminating the Annual Standard

Table D-2 shows the current status of annual average SO_2 values versus the second highest 24-hour values. Few sites exceed the current annual standard (0.03 ppm). For source (including smelter) sites, attaining the 24-hour standard would result in attaining the annual standard (Frank and Thrall, 1982). For population-oriented sites, however, most of the sites exceeding the current annual standard already meet the 24-hour standard; therefore, without an annual standard, further improvement would not be expected.

To further examine the consequences of eliminating an annual standard, Frank and Thrall (1982) examined the distribution of annual averages after: 1) adjusting levels downward to reflect attainment of the 24-hour standard, by itself or in conjunction with the current 3-hour standard (0.5 ppm) and/or the midpoint of the range of alternative 1-hour standards (0.5 ppm); and 2) allowing for limited growth up to the level of the 24-hour standard. Following these adjustments, fewer smelter sites would exceed the annual standard, but "a substantially larger number of cases exceeding the annual standard would occur, primarily among the population-oriented locations" (Frank and Thrall, 1982). The 38 population-oriented sites that would exceed the annual standard are identified in Table 18 of Frank and Thrall (1982) and include a number of heavily populated cities and counties, including New York City, Philadelphia, Cook County, IL (Chicago), and Jefferson, KY (Louisville).

TABLE D-2. CURRENT STATUS OF ANNUAL AVERAGES VERSUS SECOND-HIGHEST 24-HOUR VALUES (ppm) BY SITE TYPE (FRANK AND THRALL, 1982)

Annual Average		Second Highest 24-Hour Value (ppm)								
		Population			Source			Smelter		
μg/m^3	(ppm)	Total	< 0.14	> 0.14	Total	< 0.14	> 0.14	Total	< 0.14	> 0.14
< 60	(< 0.023)	711	710	1	498	487	11	44	39	5
61-80	(0.024-0.031)	34	34	0	12	8	4	8	4	4
81-100	(0.032-0.038)	7	6	1	1	1	0	8	3	5
> 100	(> 0.038)	1	1	0	1	1	0	4	0	4

B. Modeling Analysis

Burton et al. (1982) analyzed the relationships among alternative averaging times through air quality modeling of representative large point sources. This analysis is an important supplement to air quality data analysis because: 1) most emissions limitations for major SO_2 sources are based on modeling, rather than monitoring data; 2) monitoring sites around point sources are generally too limited to capture maximum short-term values; and 3) models can give estimates of the spatial extent of potential exposures.

The modeling analysis simulated several hypothetical power plant situations involving unscrubbed 1000 megawatt (MW) power plants with 400 foot stacks. Flat, rolling, and complex terrain settings were examined. The CRSTER and COMPLEX I models were used in modes that simulate the temporal variability in SO_2 emissions. Details of the analysis are included in the report (Burton et al., 1982). The preliminary findings are subject to uncertainties inherent in air quality modeling, apply strictly only to the few cases examined, and are sensitive to assumptions made about implementation approach and background levels. Nevertheless, they should be illustrative of relationships among averaging times for large point sources.

The major questions concern the extent to which current SO_2 standards limit peak 1-hour concentrations around major point sources. Because the annual standard is rarely controlling near large point sources (Frank and Thrall, 1982), only the 24-hour and 3-hour standards were examined in the modeling analyses. Figures D-2a and b show the geographical extent and number of expected exceedances of a 1-hour concentration of 0.5 ppm

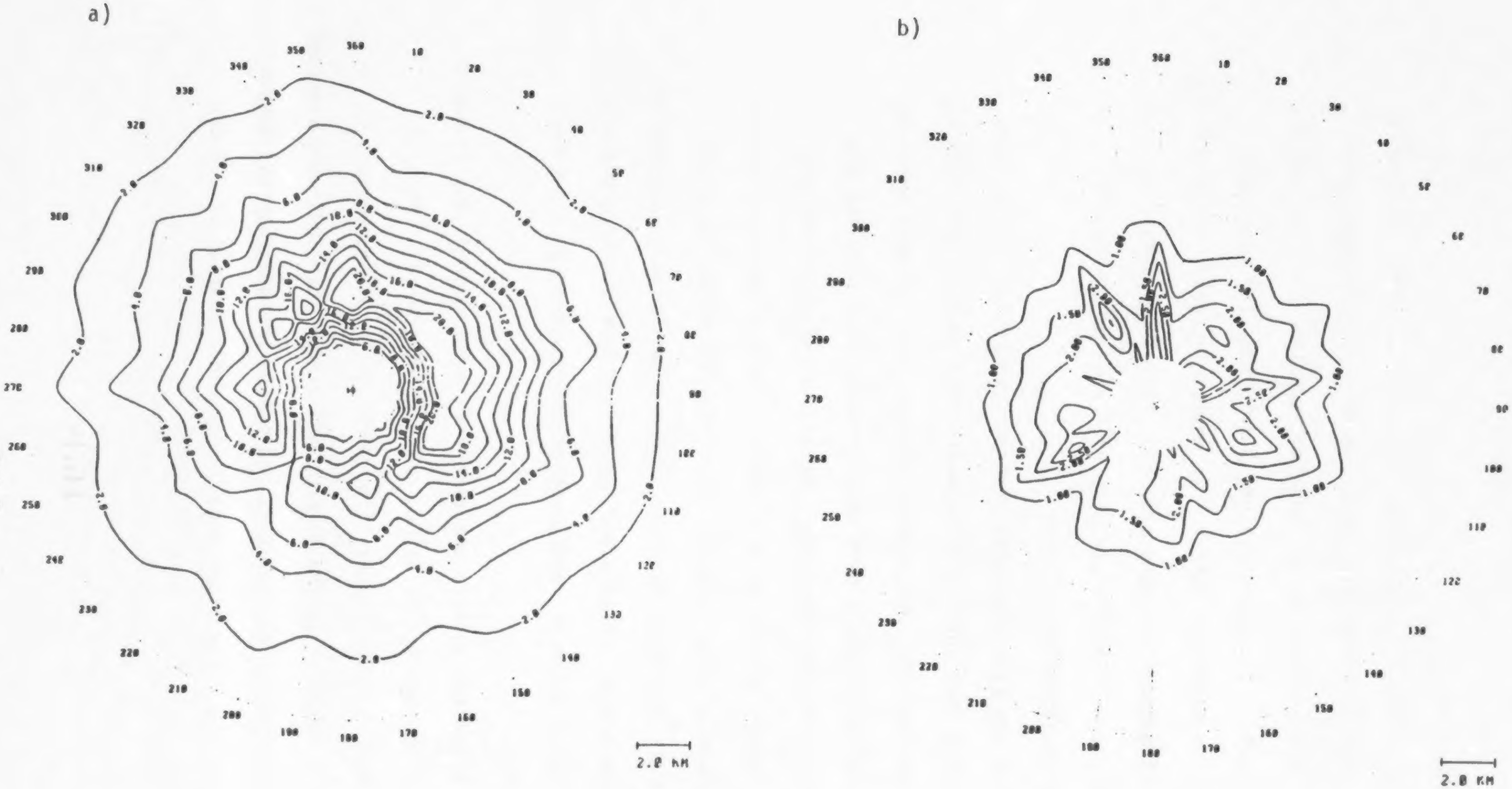

Figure D-2. Location and Number of Expected Exceedances per Year of a 1-Hour Average Value of 0.5 ppm for a 1000 MW Power Plant just complying with, a) the Current 24-Hour SO_2 Standard, and b) the Current 3-Hour SO_2 Standard (Burton et al., 1982) when the current standards are just met. Figure D-2a indicates that the current 24-hour standard would permit yearly second hourly maxima in excess of 0.5 ppm as far as 12 km (7.2 miles) from the source. Over 20 exceedances of this concentration occur in areas within 2 to 5 km of the source. Figure D-2b shows that the 3-hour standard is substantially more protective in this modeled case. Second maxima in excess of 0.5 ppm are confined to areas less than 5 km from the source with no more than 3-4 expected exceedances at any site. Figures D-3a and b show the maximum expected 5 highest concentrations for the same cases. The 24-hour standard would permit 4 exceedances of a 1-hour concentration of 0.75 ppm, while the 3-hour standard would permit only 1. The second maximum hourly concentration associated with the 24-hour standard would exceed 1 ppm, with correspondingly higher peak (5-10 minutes) values possible.

Based on this analysis, the current 24-hour standard would not prevent multiple exceedances of 1-hour values in the range of 0.25 to 0.75 ppm at distances of up to 12 km from major point sources. The current 3-hour standard provides substantially better protection against such excursions and could itself be a useful surrogate.

The above analysis was for the flat-terrain case. Available data do not suggest rolling terrain would involve substantially different conclusions. Results of complex terrain modeling are limited and less reliable. As noted previously, the results are also sensitive to a number of modeling assumptions used. In a number of routine applications, somewhat greater protection may be provided by the 24-hour standard than in this analysis.

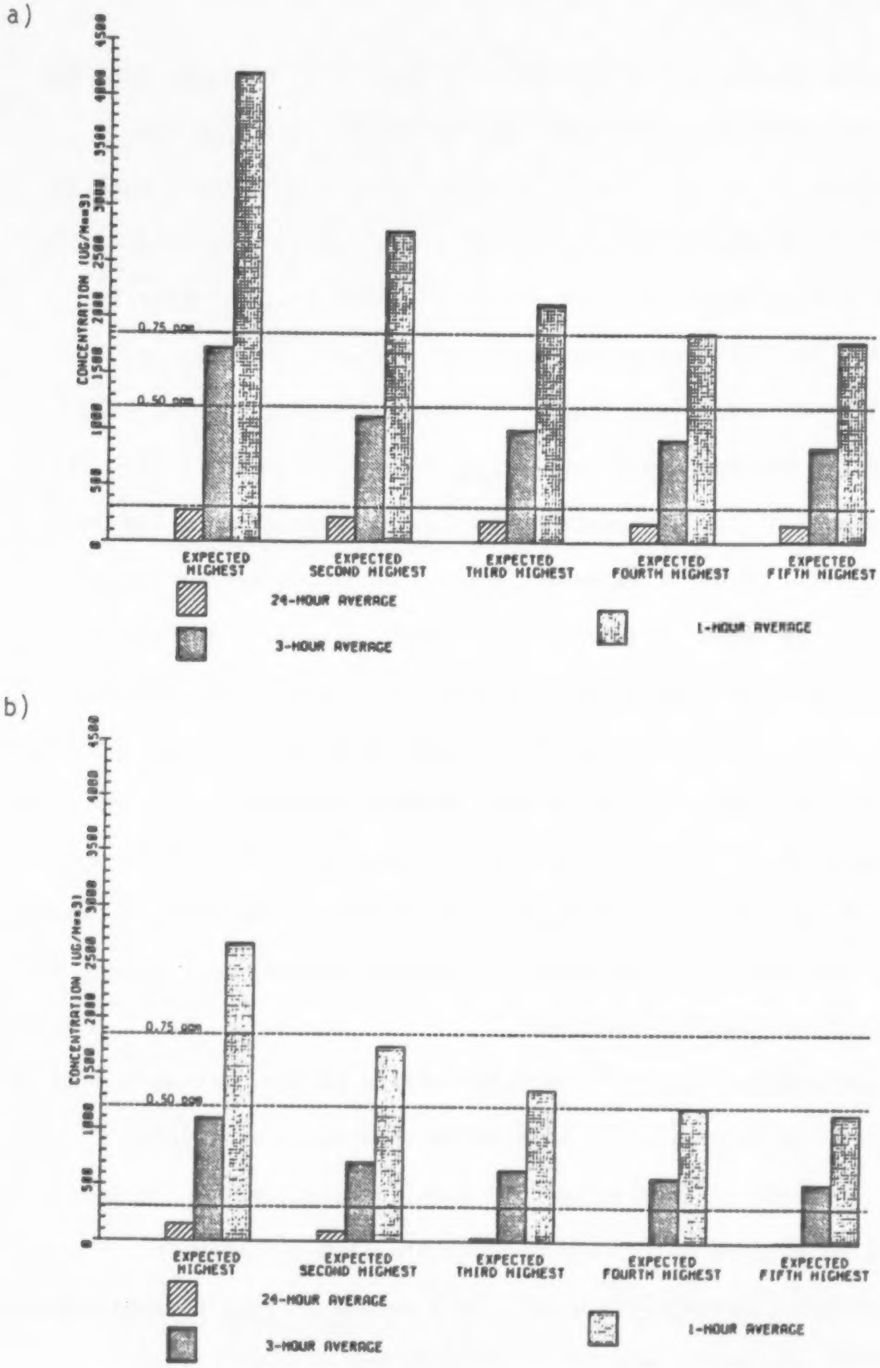

Figure D-3. Maximum 5 Concentrations for a 1000 MW Power Plant just complying with, a) the Current 24-Hour SO_2 Standard and b) the Current 3-Hour SO_2 Standard (Burton et al., 1982).

C. Exposure Analysis

A complete analysis of exposures of sensitive populations to SO_2 would involve extensive air quality simulations, analyses and modeling of activity patterns, and improved information on location and activities of sensitive groups. Available techniques for exposure analysis are currently being applied to SO_2, but no results are available. To provide some preliminary indication of exposure, the initial results of the modeling described above were used to estimate the number of individuals living in areas with potential for at least one hour per year in excess of 0.5 ppm (Anderson, 1982).

As a first approximation, a screening algorithm was used to identify those power plants that under several scenarios, might exceed 0.5 ppm for 1-hour. The census tract data was used to calculate the number of individuals living within various radii (up to 20 km) of the plants. Based on the analysis of Figure D-2, most of the exceedances of 1-hour values of interest will occur within 10 km of the source; hence, potentially exposed populations will include those living within this distance.

Assuming "current" emission rates, the algorithm indicated 77 power plants that potentially might cause exceedances of 0.5 ppm. This represents a total potential exposure of 7 to 8 million people (one person exposed to two plants is counted twice) who live within 10 km of these sources. If asthmatics and atopics comprise the same proportion as they do in the U.S. population at large (about 5 to 10%), then several hundred thousand sensitive individuals live in locations where, with current emissions they might be exposed. Because a number of sources actually emit lower amounts than needed to meet regulations, exposures would increase if each source just met its emission limits. Assuming all plants just met current SO_2

emission limitations, between 7 and 21 million people (up to 10% of the U.S. population) may live within 10 km of sources capable of causing hourly exceedances of 0.5 ppm. Thus, assuming asthmatics and atopics are distributed in geographical patterns similar to the population at large, up to 10% of the sensitive population may live in areas that would be permitted to exceed 0.5 ppm at some location, at least once per year.

The above estimates are crude and tend to overstate exposures because of 1) potential multiple counting, 2) conservative assumptions in the screening algorithm, 3) at any given plant/time, the area in excess of 0.5 ppm will be much smaller than the area of the 10 km radius circle, and 4) indoor/outdoor differences, activity patterns and the like substantially reduce the numbers of exercising asthmatics that actually encounter a peak SO_2 value.

APPENDIX E. CASAC CLOSURE LETTER

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

August 26, 1983

OFFICE OF
THE ADMINISTRATOR

Honorable William D. Ruckelshaus
Administrator
Environmental Protection Agency
Washington, D.C. 20460

Dear Mr. Ruckelshaus:

The Clean Air Scientific Advisory Committee (CASAC) has completed its second and final review of the revised draft Office of Air Quality Planning and Standards (OAQPS) Staff Paper entitled Review of the National Ambient Air Quality Standards for Sulfur Oxides: Assessment of Scientific and Technical Information.

The document is consistent in all important aspects with the scientific evidence presented and interpreted in the combined criteria document for sulfur oxides and particulate matter. It has organized the data relevant to the establishment of sulfur dioxide primary and secondary ambient air quality standards in a logical and compelling way, and the Committee believes that it provides you with the kind and amount of technical guidance that will be needed to make appropriate decisions about revisions to the standards.

During the course of the Committee's review of the Staff Paper for Sulfur Oxides a number of significant scientific issues related to the establishment of primary and secondary standards were addressed. A review of the existing data base for this pollutant led the Committee to conclude that there are two scientifically supportable options for revising the existing standards. One option for which there is strong but not unanimous support on CASAC includes the following: establishment of a new 1-hour primary standard in the range between .25-.75 parts per million, retention of a 24-hour primary standard, conversion of the current .03 ppm annual primary standard to an annual secondary standard at or below that level, and selection of a revised 3-hour secondary standard between a range of .40-.50 ppm. The other option for which there is some support on the Committee is to retain the existing primary and secondary standards, while providing some additional public health protection by converting the existing 3-hour secondary standard into a primary standard. The choice between these options is a policy decision which is not within the scope of the Committee's mission. CASAC's wishes to inform you that either of these options would be supported by the available scientific evidence.

Other scientific issues and studies of interest to the review and possible revision of the primary and secondary standards are reviewed in the attached report. In addition, I have attached a recent CASAC report on research needs for the gases and particles program within the Agency. It is clear that there are major gaps in our understanding of these pollutants and that the Agency should develop a more balanced and more adequately funded research program.

I hope the CASAC's findings and recommendations prove useful to you as you review and consider revisions to the sulfur dioxide standards. The Committee appreciates the opportunity to advise you on this important issue, and it will provide further review and comment to you during the public comment period that follows the proposal of revised standards in the Federal Register.

Sincerely,

Bernard D. Goldstein, Chairman
Clean Air Scientific Advisory
Committee

Attachment

cc: Alvin Alm
Charles Elkins
Terry F. Yosie

Findings, Recommendations and Comments of the Clean Air Scientific Advisory Committee on the OAQPS Revised Draft Staff Paper for Sulfur Oxides

CASAC's evaluation of the scientific basis for a review and possible revision of the ambient air quality standards for sulfur dioxide began with its recommendation in November 1978 that the Agency evaluate the joint interaction of sulfur oxides and particulate matter on human health and the environment by the development of a joint criteria document for these pollutants. Following three public reviews of the criteria document and its subsequent revision by Agency staff, the Committee concluded in a letter to the Administrator dated January 29, 1982 that the Agency's assessment of the existing literature for these pollutants was scientifically adequate. This report addresses the OAQPS staff's interpretation of the criteria document and the scientific rationale that is develped to support their proposals for reviewing and revising the SO_2 standards.

The Scientific Basis for Primary SO_2 Standards

1. A major OAQPS conclusion of the criteria document review process was that sulfur dioxide continued to pose a serious health problem to important subgroups of the population which warranted its continued separate control. Thus, OAQPS does not recommend a joint SO_2/particles primary standard, believing that current information on health effects and U.S. exposures to these two pollutant categories warrants a continuation of separate controls.

CASAC concludes that separate SO_2 and particles standards, each set with appropriate consideration for potential interactions, does appear to protect public health. Furthermore, the complexities of setting and implementing a joint SO_2/particles standards through monitoring and other requirements create numerous uncertainties which the available scientific evidence is ill-equipped to resolve. CASAC concurs with the OAQPS position and its supporting rationale and recommends that you retain the current approach of setting separate primary and secondary standards for sulfur dioxide and particulate matter.

2. The scientific basis for a 24-hour standard stems primarily from epidemiological studies. These studies (Lawther et al. 1970 [analysis of bronchitics]; Martin and Bradley, 1960, Mazumdar et al., 1981, and Ware et al., 1981 [analysis of mortality]) do not show evidence of clear thresholds, but they suggest that risk to public health increases as concentration levels increase. The Air Quality Criteria Document for Sulfur Oxides/Particulate Matter and the SO_2 staff paper interpret these studies as suggesting that increases in excess mortality occurred in the range of 500-1000 ug/m^3 British Smoke and .19-.38 ppm SO_2, and that such effects are most likely when both pollutants exceeded 750 ug/m^3 (.29 ppm SO_2). Lawther's study of reported symptoms among bronchitics also suggests that this population group experiences significant responses associated with 24-hour averages of .19 ppm SO_2. Based

upon these studies and the need for a margin of safety the staff paper developed a range of interest between .14 to .19 ppm in recommending a revised 24-hour primary SO_2 standard.

The upper end of the recommended range of .14 to .19 ppm represents a level at which effects are identified in the criteria document and for which there is little or no margin of safety for exposed sensitive individuals. You should be aware that the ranges of interest developed in the staff paper for the 24-hour standard were based on epidemiological studies which provided quantitative concentration/response data of the populations studied. A final decision on whether or not to revise the 24-hour standard should also incoporate information generated through controlled human, animal toxicology and the less quantitative epidemiology studies discussed in the criteria document and staff paper. In view of all of the above, CASAC recommends that you consider selecting a value at the lower end of the range for the 24-hour standard, taking into account whether a separate 1-hour primary standard is also established.

3. CASAC's review of the scientific evidence related to the annual primary standard presents a dilemma because the Committee could find no real quanitative basis for retaining this standard. This is a troublesome issue because there is the possibility that repeated SO_2 peaks of 1-hour and 24-hour exposures might lead to effects on human respiratory systems

over the long-term. Second, an annual primary standard affords protection against health effects that can't be measured well in short-term controlled human studies. Third, air quality analysis conducted by OAQPS staff suggests that 1-hour and 24-hour primary standards in the range stated in the staff paper would not prevent SO_2 concentrations from exceeding the current annual primary standard in some heavily populated areas of the country. Fourth, as pointed out in the discussion of secondary standards, there is a scientific basis for a secondary standard at the level of the annual current primary standard. Following extended discussion the Committee concluded that some protection against chronic SO_2 exposures is needed, but that the most persuasive scientific basis for an annual standard is found in the effects on welfare.

4. The scientific basis for the development of a 1-hour primary standard rests largely on several major controlled human clinical studies conducted by three separate laboratories that were published in the peer reviewed literature in 1981 and 1982. These studies documented measurable changes in respiratory function of exercising asthmatics exposed for short periods at or below concentration levels of .50 parts per million (ppm). The studies (Kirkpatrick et al. 1982; Koenig et al. 1982; Linn et al. 1982; and Sheppard et al. 1981) raise

the issue of how adequately the existing primary standards are protecting public health and provide a scientific basis for a 1-hour primary standard that provides additional protection against such reported short-term effects.

The OAQPS staff, after reviewing this data, proposed consideration of a 1-hour primary standard in the range between .50 to .75 ppm. The staff noted that the lower end of the range represented the lowest level where potentially significant responses in asthmatics have been observed with oronasal breathing, and that the upper bound of the range represented levels at which the risk of significant functional and symptomatic responses in exposed asthmatics and other sensitive groups appeared high.

CASAC has evaluated the OAQPS staff position that resulted in the establishment of the range of interest at .50-.75 ppm. The staff suggest that there may be little or no margin of safety at the upper bound of the range. Air quality analyses conducted by OAQPS also indicate that a 1-hour standard selected from within the range would still permit exposures in excess of one to two ppm during the peak five or ten minute intervals. A related point is that establishment of a 24-hour standard in the range of .14-.19 ppm would not necessarily protect against shorter term peaks above the proposed 1-hour range of .50-.75 ppm. This information suggests that a 1-hour primary standard selected between .50-.75 ppm range might not adequately protect sensitive populations with an adequate margin of safety from the effects acknowledged in the staff paper that would occur as a result of brief peak exposures to concentrations greater than the .50-.75 ppm hourly average that a 1-hour standard would permit. Because five to ten minute peaks can reach levels as much as two or more times the 1-hour average, CASAC recommends that the range be modified to state the lower bound at .25 ppm.

In reviewing the issue of whether to establish a 1-hour primary standard between .25-.75 ppm several additional factors should be considered. These include 1) it is not clear that the reported effects experienced at or below .50 ppm are significant. The functional changes and symptoms reported in the .50-.75 ppm range appear to be reversible. You will need to determine which effects you consider to be adverse; 2) it is probable that some asthmatics are more sensitive than those who took part in the studies; 3) given current air quality conditions there is a low probability of exposure to exercising asthmatics at peak concentration levels; and 4) as the staff paper suggests, other stimuli interacting with SO_2, such as temperature and humidity, may increase the risk of an attack to exercising asthmatics more than either of these factors acting alone.

The Scientific Basis for Secondary SO_2 Standards

The kinds of effects reviewed by CASAC in relation to the establishment of secondary ambient air quality standards include those on vegetation, materials, and acidic deposition.

1. Current scientific information documents effects on vegetation resulting from both short-term and long-term exposures to SO_2 and/or SO_2 in combination with other pollutants. One should keep in mind that there is no single concentration at which all species of plants are injured, just as there is not single point or threshold at which all humans suffer significant effects from SO_2. What is at issue in the development of secondary standards is the need to protect sensitive vegetative species from effects such as physiological and biochemical changes, foliar injury, and reduced growth and yield. The available studies of SO_2 effects on vegetation represent approximately one percent of total plant species, but they include such important species as soybeans, barley, and white pine, to name a few.

An issue of increasing concern in the protection of vegetation is that SO_2 is not present alone in the ambient air except at a few isolated point sources. It almost invariably occurs in the presence of other pollutants, primarily nitrogen oxides and ozone. The scientific evidence is conclusive that the combination of such pollutants is more damaging to vegetation than the presence of SO_2 alone.

The staff paper recommends consideration of a 3-hour standard at or below the current secondary standard level of .50 ppm to protect vegetation. Although there are reports in the literature concerning plant injury at .10 to .20 ppm averaged over several hours, there are great uncertainties associated with the effects of the exposures at these lower levels. The existing data on the acute effects of SO_2 on vegetation suggest to CASAC that a concentration limit selected within a range of .40 to .50 ppm for a 3-hour period would provide adequate protection to sensitive vegetative species.

The review of longer term effects on plants was hampered by a very limited data base, thus making it difficult to distinguish whether such effects resulted from chronic lower-level exposures or a series of shorter-term peak exposures. Available data do suggest, however, that changes in species diversity and reduced growth in vascular plants are effects that may occur over the long term. In addition, non-vascular plants, particularly lichens and mosses, are affected by SO_2 during prolonged periods of exposure. On the basis of scientific work conducted to date, CASAC concurs with the OAQPS staff recommendation that an annual secondary standard at or below .03 ppm (a level equivalent to the existing annual primary SO_2 standard) would afford adequate protection to vascular plant vegetation. The basis for concern over effects in non-vascular plants at lower levels needs to be strengthened. CASAC also agrees with the staff proposal to address this issue in the context of later action on fine particles and acidic deposition.

2. The action of SO_2 alone or in combination with other pollutants has been associated with a number of damages to building materials, corrosion of ferrous and non-ferrous structures, and impairment of other goods and materials.

OAQPS staff have reviewed the evidence documenting materials damage from SO_2. These effects are responsible for economically significant losses which have been adequately summarized in both the criteria document and the staff paper. Analyses of existing air quality data by OAQPS indicate that continued protection against SO_2-induced materials damage is needed, and toward that end, the staff paper recommends consideration of a long-term SO_2 standard at or below the level of the existing annual primary standard (.03 ppm). CASAC concurs with the staff recommendation.

3. Throughout its review of both the Air Quality Criteria Document for Sulfur Oxides/Particulate Matter and the Staff Paper for Sulfur Oxides, CASAC has recognized the complexity of the acidic deposition problem. Since SO_2 is only one of the

precursor pollutants that lead to the formation of acidic deposition, CASAC recommended in August 1980 that EPA prepare a separate Critical Assessment Document that recognizes and incorporates information on causes, effects and data bases for all of the various pollutants relevant to acidic deposition. This CASAC recommendation was accepted by two previous Administrators, Douglas Costle and Anne Burford, and the assessment document should be available for CASAC review in the near future. At that time the Committee will be in a position to provide a more comprehensive and critical assessment of the acidic deposition problem.

Re-affirmation of the Existing Primary and Secondary Standards

Throughout its review of the staff paper, CASAC recognizes that large uncertainties exist in the data that support development of the options for setting the standards discussed in the previous pages. Given these uncertainties CASAC discussed the extent to which the existing standards provide adequate protection to the public health. The Committee recognizes the substantial improvements in air quality that have occurred since the 1971 promulgation of the primary SO_2 standards. In addition, more information on the effects of the short-term SO_2 exposures should become available in the peer reviewed literature in the next few years. Air quality modeling analyses also suggest that attainment of the proposed 24-hour and annual standards would not ensure complete attainment of the proposed 1-hour primary standard at all sites within the ranges of interest stated. The reverse also appears to be true.

CASAC's evaluation of the scientific evidence associated with existing averaging times in the staff paper leads the Committee to conclude that continuation of the existing primary and secondary standards also provides protection aganist the effects identified in the criteria document and staff paper from SO_2 at ground level. If you choose to follow this option some CASAC members suggest that additional health protection can be obtained by converting the existing 3-hour secondary standard into a primary standard. A principal argument supporting the latter is that since the states are already implementing a 3-hour secondary standard, conversion to a 3-hour primary standard would not be impractical. In summary, in view of the many uncertainties that pertain to the review of the SO_2 standards, retention of the existing set of primary and secondary SO_2 standards is an option that you ought to seriously consider at the present time.

Conclusion

CASAC recognizes that your statutory responsibility to set standards requires public health policy judgments in addition to determinations of a strictly scientific nature. The submission of this closure letter completes the Committee's scientific assessment of this pollutant and we see no need to provide any additional formal comments on the standards prior to their proposal in the Federal Register. The public comment period will then provide sufficient opportunity for the Committee to provide any additional comment or review that may be necessary.

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